REPSOL NUEVAS ENERGIAS UK LIMITED

REGIONAL COASTAL PROCESSES BASELINE DESCRIPTION

INCH CAPE AND NEART NA GAOITHE OFFSHORE WIND FARMS

Report Reference. P1476_RN2728_Rev0

Issued 9 September 2011

Metoc Limited
Exchange House
Liphook
Hants GU30 7DW
United Kingdom

Tel: +44 (0) 1428 727800
Fax: +44 (0) 1428 727122

E-mail: info@metoc.co.uk
Web Site: www.metoc.co.uk

DOCUMENT RELEASE FORM

Title:	REGIONAL COASTAL PROCESSES BASELINE DESCRIPTION INCH CAPE AND NEART NA GAOITHE OFFSHORE WIND FARMS
Client:	REPSOL NUEVAS ENERGIAS UK LIMITED
Report Reference:	P1476_RN2728_REV0
Date of Issue:	9 September 2011

		Hard Copy	***Digital***
Distribution:	REPSOL NUEVAS ENERGIAS UK LIMITED	No:	
	Intertek METOC	No:	
Prepared By:	Paul Taylor, Kevin Black		

Project Manager:	Authoriser:
Paul Taylor	Chris Mooij

Rev No	***Date***	***Reason***	***Author***	***Checker***	***Authoriser***
Rev 0	09/11/2011	Original	PAT/KB	KRM	CPM

COPY NUMBER: (applies to hard copies only)

Intertek METOC is the trading name of Metoc Ltd, a member of the Intertek group of companies

SUMMARY

Repsol Nuevas Energias UK Limited (RNEUK) has commissioned Intertek METOC to undertake assessments of meteorological/oceanographic (metocean) and coastal processes on behalf of the Forth and Tay Offshore Wind Developers Group (FTOWDG). The studies relate to the Forth and Tay Offshore Wind Farm (OWF) developments at Inch Cape and Neart na Gaoithe, in Scottish Territorial Waters (STW). RNEUK is developing the Inch Cape OWF, whereas the Neart na Gaoithe OWF is being developed by Mainstream Renewable Power Ltd (Mainstream).

This document presents an overview of the baseline (existing) meteorological, oceanographic and coastal processes environment at a regional level. The review builds upon earlier work by HR Wallingford (2009a) and information contained within the respective Scoping Reviews (Inch Cape and Neart na Gaoithe), but is expanded and modified through inclusion of new data and new analysis. A wide variety of currently available sources have been used in this regional assessment, including field data collected during the bespoke survey campaigns commissioned by the developers, and outputs from the hydrodynamic, spectral wave and sediment modelling system that has been developed specifically for this assessment.

This regional baseline report includes an assessment of the:

- Meteorology;
- Bathymetry;
- Geology and surficial sediment cover (including sediment features or bedforms, and broad-scale sediment transport patterns);
- Physical oceanographic conditions (including general water circulation patterns); and
- Sediment regime (including fluvial inputs, shoreline processes and coastal cells).

CONTENTS

TABLES

FIGURES

GLOSSARY

BERR	Department for Business, Enterprise and Regulatory Reform
BODC	British Oceanographic Data Centre
BSG	British Geological Society
CD	Chart Datum
Cefas	Centre for Environment, Fisheries and Aquaculture Science
DEFRA	Department for Food, Rural and Environmental Affairs
DTI	Department of Trade and Industry
EIA	Environmental Impact Assessment
FRS	Fisheries Research Service
FTMS	Forth and Tay Modelling System
FTOWDG	Forth and Tay Offshore Wind Developers Group
FWR	Foundation for Water Research
HAT	Highest Astronomical Tide
HD	Hydrodynamic Model
HRCS	High Resolution Continental Model
LAT	Lowest Astronomical Tide
MHWN	Mean High Water Neaps
MHWS	Mean High Water Springs
MSL	Mean Sea Level
ODN	Ordnance Datum
OWF	Offshore Wind Farm
POL	Proudman Oceanographic Laboratory
RNEUK	Repsol Nuevas Energias UK Limited
SEPA	Scottish Environmental Protection Agency
SNH	Scottish National Heritage

STW	Scottish Territorial Waters
SW	Spectral Wave Model
UKCIP	UK Climate Impacts Programme
UKHO	UK Hydrographic Office
UKMO	UK Met Office

1 INTRODUCTION

1.1 BACKGROUND

Repsol Nuevas Energias UK Limited (RNEUK) has commissioned Intertek METOC to undertake assessments of meteorological/oceanographic (metocean) and coastal processes relating to Scottish Territorial Waters (STW), Forth and Tay Offshore Wind Farm (OWF) developments at Inch Cape and Neart na Gaoithe. RNEUK is developing the Inch Cape OWF, whereas the Neart na Gaoithe is being developed by Mainstream Renewable Power Ltd (Mainstream).

These developments will potentially affect both the metocean and coastal processes regimes in and around the development areas. Effects may range from short to long term, and the assessment will consider timescales up to 25 years. The OWF developers require an understanding of the magnitude and significance of these effects, with a view to implementing, where necessary, appropriate mitigation measures in order to minimise impacts.

The study requires the delivery of a calibrated and validated coastal hydrodynamic (HD) and spectral wave (SW) model, and the delivery of a coastal processes assessment using the models and available information. The proposed assessments will provide the developers and other stakeholders with the regional and site-specific characterisation of the metocean and physical geomarine environment. This will allow the baseline environmental conditions to be determined, against which the effects of each individual development, and the in-combination and cumulative effects of all developments can be assessed. The study results will provide input into the Technical Report and the required Environmental Impact Assessment (EIA) for each development.

This document presents an overview of the baseline (existing) meteorological, oceanographic and coastal processes environment at a regional level (defined in Section 1.2). This review builds upon earlier work by HR Wallingford (2009a) and information contained within the respective Scoping Reviews (Inch Cape and Neart na Gaoithe), but is expanded and modified through inclusion of new data and new analysis. A wide variety of currently available sources have been used in this regional assessment (Table 2-1), including outputs from the HD and SW modelling system that has been developed specifically for this assessment.

This document presents summary reviews on the following topics:

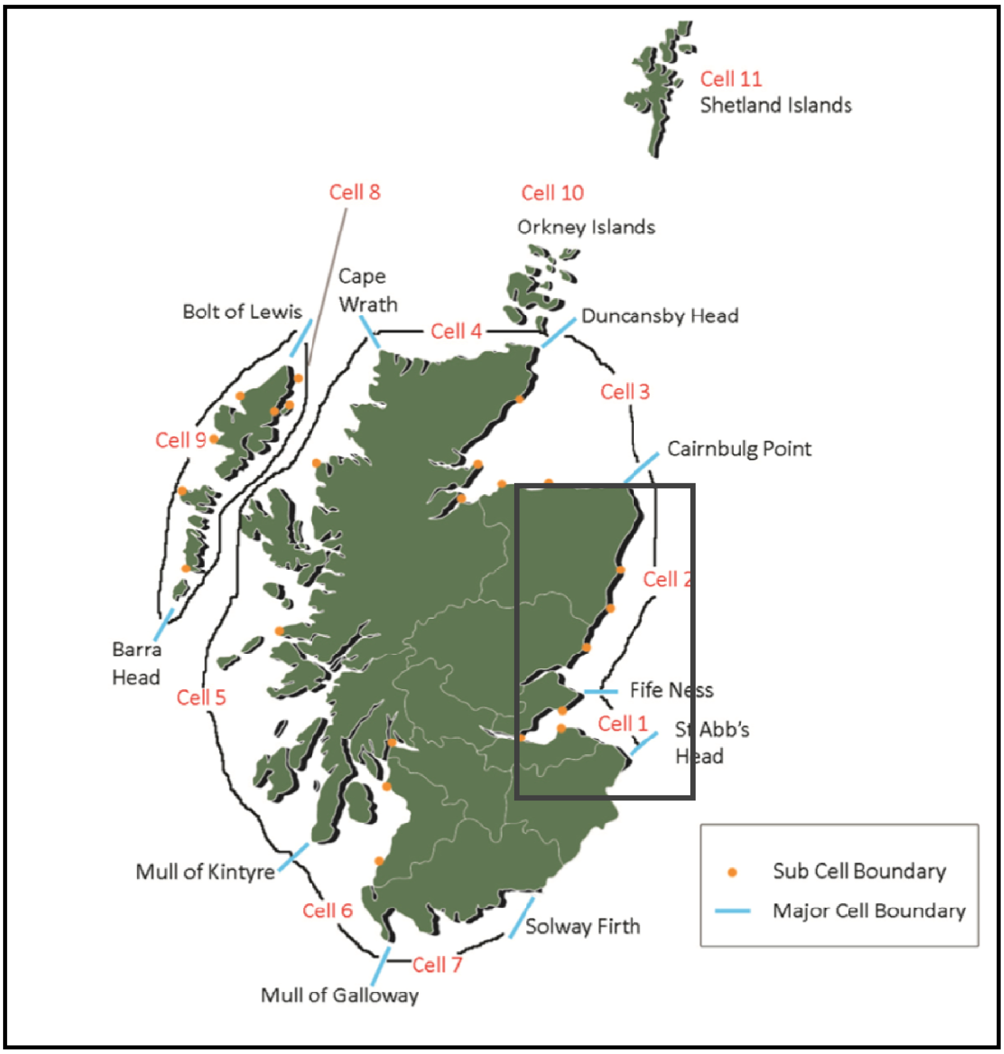
- Section 3 Regional meteorology;
- Section 4 Bathymetry;
- Section 5 Geology and surficial sediment cover, including sediment features (bedforms) and broad-scale sediment transport patterns;
- Section 6 Physical oceanographic conditions, including general water circulation patterns; and
- Section 7 Sediment regime, including fluvial inputs, shoreline processes and coastal cells.

1.2 DEFINITION OF THE REGIONAL EXTENT

It is important to place the proposed development sites within a regional context in terms of their geological and oceanographic characteristics. This allows for an understanding of the wider geographical context of the sites, and acts as a frame within which individual baseline assessments for each proposed development can be considered.

For present purposes the term ‘regional’ is defined as the marine offshore region extending from St Abbs Head (England) to Cairnbulg Point (NE Scotland) and extending eastwards to the eastern boundary of the proposed Crown Estate Zone 3 zone (Figure 1-1). This area spatially embraces the two OWF sites on a scale which encompasses the potential for cumulative effects of construction at the Z3 area, and is defined at the shoreline by coastal cell boundaries. On occasion the sub-cell boundary at Deil’s Head (Angus) is used to delimit the description of shoreline processes. The western limit for consideration is the Forth Road Bridge.

Figure 1-1 : Definition of the boundaries for the ‘regional’ baseline description



Note: The regional area is shown by the box and is framed within the context of the coastal cells. Map based upon Ramsay and Brampton (2000a, b).

2 DATA SOURCES

A wide variety of currently available sources have been used in the production of this regional baseline assessment. A major resource is the earlier work by HR Wallingford (2009a) and the respective Scoping Reviews for each development site (Inch Cape and Neart na Gaoithe). British Geological Society (BSG) regional volumes on geomarine processes and regional geological attributes (Gatliff *et al*., 1994; Pantin, 1991) have been especially useful. Table 2-1 summarises the principal data sources used.

Table 2-1 : Summary of major data sources used

Data Source	Study/Data Name	Data Theme(s)	Data Location
Mainstream / RNE UK	Scoping Studies	Environmental baseline	At site
HR Wallingford reports	Firth of Forth Water Quality Model Assessment of Field Data Scoping Support (2009) Various background reports (engineering and survey design)	Water quality (turbidity) Baseline	East coast of Scotland/At site
SENERGY	Geotechnical overview report	Sedimentology; geotechnics	At Inch Cape site
Partrac	Metocean monitoring data	Metocean monitoring data (waves, tides, wind)	At site
JNCC UK SeaMap	SeaMap 2010	Seabed habitats/landscapes	East coast of Scotland
Scottish National Heritage (SNH)	Coastal Cells in Scotland Cell 1 St Abb's Head to Fife Ness Cell 2 Fife Ness to Cairnburg Point	Shoreline processes	East coast of Scotland
British Geological Society (BGS)	1986. Tay Forth, Sheet 56°N-04°W, Seabed Sediments, 1:250,000 series. 1987. Tay Forth, Sheet 56°N-04°W, Quaternary Geology, 1:250,000 series. 1986. Tay Forth, Sheet 56°N-04°W, Solid Geology, 1:250,000 series. General – geology and sediment maps; Holmes (1994); Holmes et al (1999) Pantin (1991); Gatliff et al., (1994) Core archive Surface grab sample archive (www.bgs.ac.uk)	Geology, sedimentology, sediment features, sediment thickness and sediment transport	Tay and Forth
UK Hydrographic Office (UKHO)	Various contemporary charts (Admiralty Charts 175 and 190); Tide Tables, Co-tidal Charts	Bathymetry & tidal streams, water levels	East coast of Scotland
British Oceanographic Data Centre (BODC)	Data Inventory Deployments	Current measurements	Various port sites

Data Source	Study/Data Name	Data Theme(s)	Data Location
		Wave measurements Surge data	
Scottish Environmental Protection Agency (SEPA)	River Inflows	Freshwater/sediment inputs	Major rivers
Cefas WaveNet	Data Inventory	Wave measurements	Directional waverider information from WaveNet from 19 August 2008 at 56^0 11.33'N. 2^0 30'W
UK Met Office (UKMO)	Data summary	Meteorological data	Eastern Scotland
Coastal Councils	SMPs	Shoreline processes, coastal processes	Tayside; Fife; East Lothian; Angus
Department of Trade and Industry (DTI) - Department for Business, Enterprise and Regulatory Reform (BERR)	SEA3, SEA 5; 2007/07 Atlas of Renewable Energy	Regional geomarine assessment; synoptic oceanographic parameters	Regional
UK Offshore Energy SEA (DECC 2009)		Regional geomarine assessment	Regional
Scottish Marine Renewables SEA (Faber Maunsell and Metoc 2007)		Regional geomarine assessment	Regional
The Tay Estuary Coastal References Database		Geology; sedimentology; fluvial flows	Tay and Forth
Intertek METOC	The Forth and Tay HD and SW Modelling System developed specifically for this assessment	Metocean (hydrodynamic and spectral wave conditions)	Regional and site-specific

3 FORTH AND TAY MODELLING SYSTEM

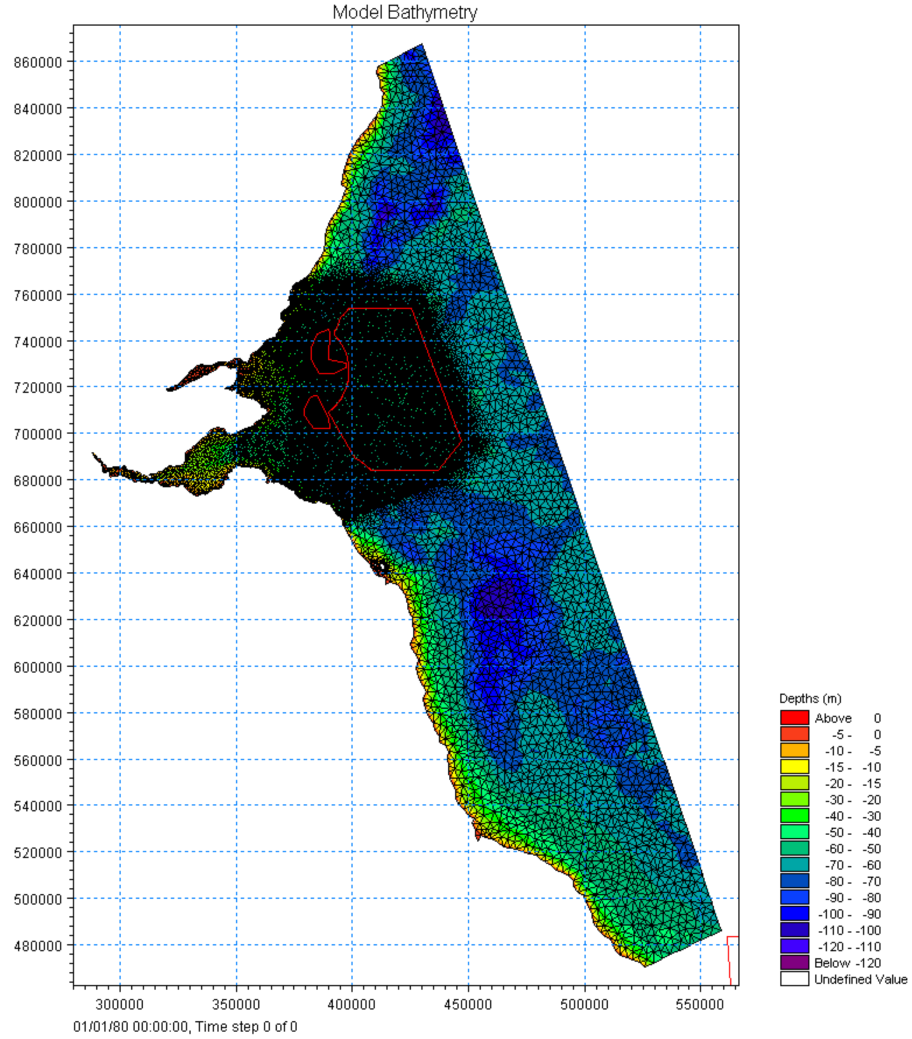
A key requirement of the coastal processes assessment was the development of a dedicated hydrodynamic and spectral wave model. Intertek METOC has constructed, calibrated and validated the Forth and Tay Modelling System (FTMS) (Figure 3-1) for the purpose of modelling the baseline metocean conditions, and any subsequent changes to the metocean regime in both the near and far-field resulting from the developments.

The FTMS has been constructed using an unstructured flexible mesh dynamic modelling system. This is a sophisticated two-dimensional modular based modelling system, and has the capacity to run hydrodynamic, spectral wave and sediment models. It may be used to predict the physical properties of tidal currents and waves, and the interactions between these, for any specified area.

A flexible mesh model has the advantage of using a spatially varying resolution, so that the complex bathymetries and coastal topographic features can be sufficiently resolved by the model. It also allows fine resolution to be configured in the key areas of interest (for instance around the OWF sites), whilst a coarser resolution can be employed in areas that do not require or warrant such fine detail (such as in the deeper waters closer to the open water boundaries).

The FTMS was built with a spatial resolution varying from approximately 60 m in the area of interest to approximately 2500 m offshore. A total of 131,582 triangular elements are used in the model. This allows adequate representation of the physical processes. The model covers an area of 33,462 km^2. Figure 3-1 shows the model domain of the FTMS.

Figure 3-1. Forth and Tay Modelling System (FTMS) model domain and mesh resolution



3.1 Model Calibration/Validation Process

3.1.1 Hydrodynamics

The hydrodynamic model was calibrated by comparing model output against field data for spring tide conditions, and validated by comparing model performance with neap tide data.

For each model run, calibration was undertaken primarily by varying the bed roughness coefficient within the model.

The model performance was assessed using guidelines set out in a number of technical reports (e.g. the Foundation for Water Research (FWR) Framework, and SEPA Standards for Models). These guidelines are accepted by Environmental Regulators and the UK Water Industry, among others. Intertek METOC has also employed its own experience gained from successfully developing a wide range of models over many years.

3.1.2 Spectral Waves

The spectral wave model was calibrated by comparing model output against field data for three different wave conditions: two representative onshore storm events (one approaching from the east and one from the north), and one offshore wind-driven event (winds primarily from the southwest). Validation was undertaken using two independent wave events: one offshore wind-driven event, and one onshore storm event.

Model calibration was undertaken primarily by varying the white capping parameters, in order to improve model performance in terms of predicted wave heights and periods. Modelled output of significant wave height, peak wave period, and wave direction were compared with the equivalent parameters obtained from five wave buoys.

There are no general guidelines for the assessment of wave model performance, as there are for hydrodynamic models. Assessment was therefore based on visual analysis, and on our modelling and oceanographic experience and expertise.

The primary sources of field data were the dedicated metocean survey campaign undertaken by Forth and Tay Offshore Wind Developers Group (FTOWDG), together with other existing field data held by the British Oceanographic Data Centre (BODC), Proudman Oceanographic Laboratory (POL) and Centre for Environment, Fisheries and Aquaculture Science (Cefas).

3.2 MODEL PERFORMANCE

The FTMS hydrodynamic model is well calibrated and validated against appropriate field data, and has been demonstrated to be performing excellently across the model domain.

The FTMS spectral wave model is also well calibrated and validated against appropriate field data, and has been demonstrated to be performing within acceptable limits across the model domain.

The FTMS is therefore fit for the purpose of undertaking the coastal processes assessment for the Inch Cape and Neart na Gaoithe OWFs.

Full details of the FTMS model construction, calibration and validation is provided in the Intertek METOC report RN2636 (2011).

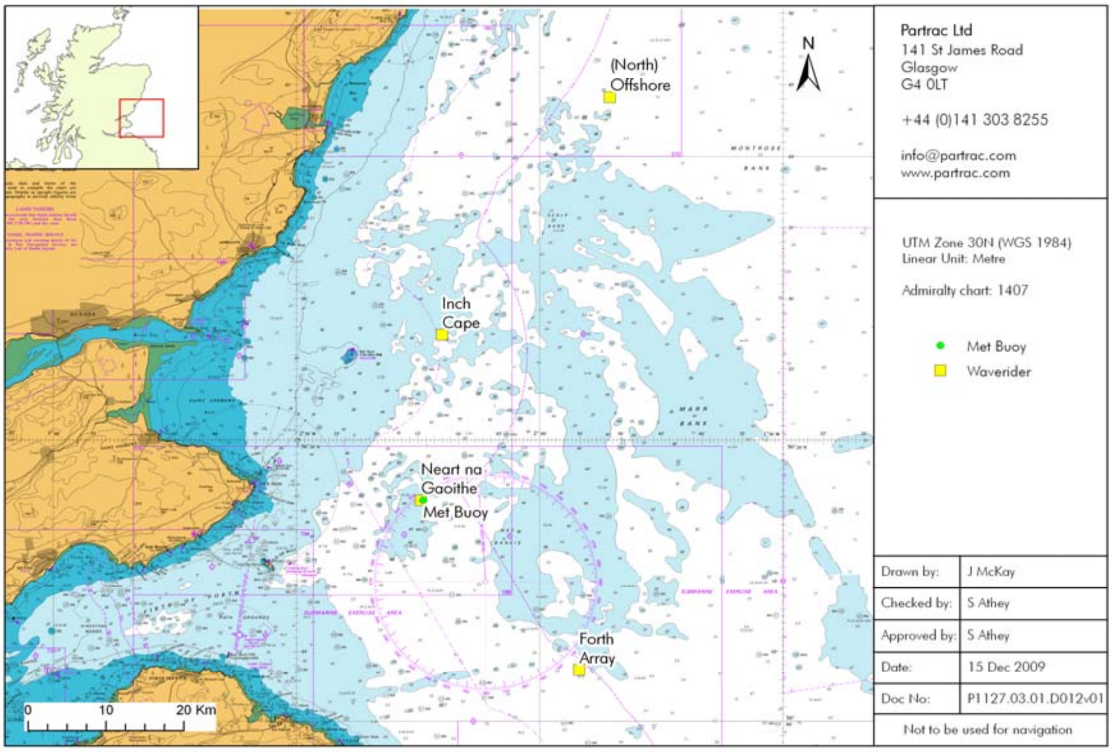
4 REGIONAL METEOROLOGY

The general meteorology of the outer Firths region is well understood. It is our understanding that preliminary wind resource evaluations have been conducted by the developers of the Forth Array (now defunct), Inch Cape and Neart na Gaoithe. However, at present we do not have access to this information. A detailed assessment of the regional conditions is provided by Harrison (1987) and additional data is given by Wal and McManus (1993). The following overview of the regional meteorology is based upon a) data collected by the FTOWDG consortium at an offshore wave buoy location (see Figure 4-1); and b) from regional UK Meteorological Office data sources.

4.1 OFFSHORE MONITORING DATA

Data have been collected by the FTOWDG consortium at an offshore wave buoy location (see Figure 4-1) as part of the FTOWDG oceanographic monitoring campaign. The wave buoy was located at: 56º 15.718 N, 002º 14.043 W and data exist between 11.12.09 - 26.6.10. Table 4-1 summarises statistics from this monitoring. Figures 4-1 and 4-2 present time-series plots for the monitoring period.

Figure 4-1 : Location of the offshore meteorology buoy deployed during the metocean monitoring campaign.



Source: Oceanographic survey

Table 4-1: Summary of statistics for key meteorological parameters from the metocean survey campaign

Parameter	Minimum	Average	Maximum
Wind Direction (º) – Dominant Direction	SSW (58.2 %)		
Wind Speed (ms^{-1})	0.3	5.9	25.1
Air Temperature (ºC)	1.2	6.9	12.8
Air Pressure (hPa)	985.5	1034.5	1013.5

Note: This data has been taken from the entire monitoring period (11/12/09 – 24/06/10, but does not include the period 28/03/10 to 12/04/10).

Eastern Scotland is one of the more windy parts of the UK, being relatively close to the track of Atlantic depressions. The strongest winds are associated with the passage of deep areas of low pressure close to or across the UK. The wind data largely reflect these weather patterns moving through the coastal zone. Average wind speed during the metocean campaign was ~6 ms^{-1} (Figure 4-1), which is regarded approximately as a median regional wind speed value (Callum *et al*., 1997) but this increased significantly during low pressure with maximum recorded wind speeds around 25 ms^{-1}. Callum *et a*l., (1997) indicate that the majority of low and intermediate wind speeds are associated with south-westerly and easterly/north-easterly winds; higher wind speeds (>11 ms^{-1}) mainly have a south-westerly origin, with isolated events from the northeast. Superimposed on the variability there is a general decrease in average and maximum wind speeds through the winter to spring-early summer transition.

Summary directional wind data are shown in Figure 4-2 which indicates winds from all directions through the monitoring period but with a general (albeit slight) dominance from the west (NW-W-SW). This is consistent with the area being exposed to westerly airstreams that move in from the Atlantic Ocean. The strongest recorded winds are from the NW. The data here are overview summaries, and individual data reports document differences in dominant wind direction from winter through to June, 2010, but these trends are hidden in the presentation of data as a summary. Generally during winter months westerly airflows dominate, whereas during summer months westerly airflows make up ~50 % of the air movements with north-easterly and easterly airflows occurring ~35 % of the time (Callum *et al.*, 1997).

Figure 4-3 shows the time series for wind speed and direction recorded by the Metbuoy during the winter period from December 2009 to June 2010, which is consistent with the summary data.

Figure 4-4 shows the time series for air temperature and pressure. Seasonal changes are evident with temperature rising steadily throughout the monitoring period from around 2 ºC to 12 ºC. There is a similar, general rise in air pressure through time from winter into the late spring-early summer months, and the record shows successive periods of low-high pressure which reflects the regional weather patterns.

Figure 4-2. Metbuoy wind rose of average wind direction and average wind speed

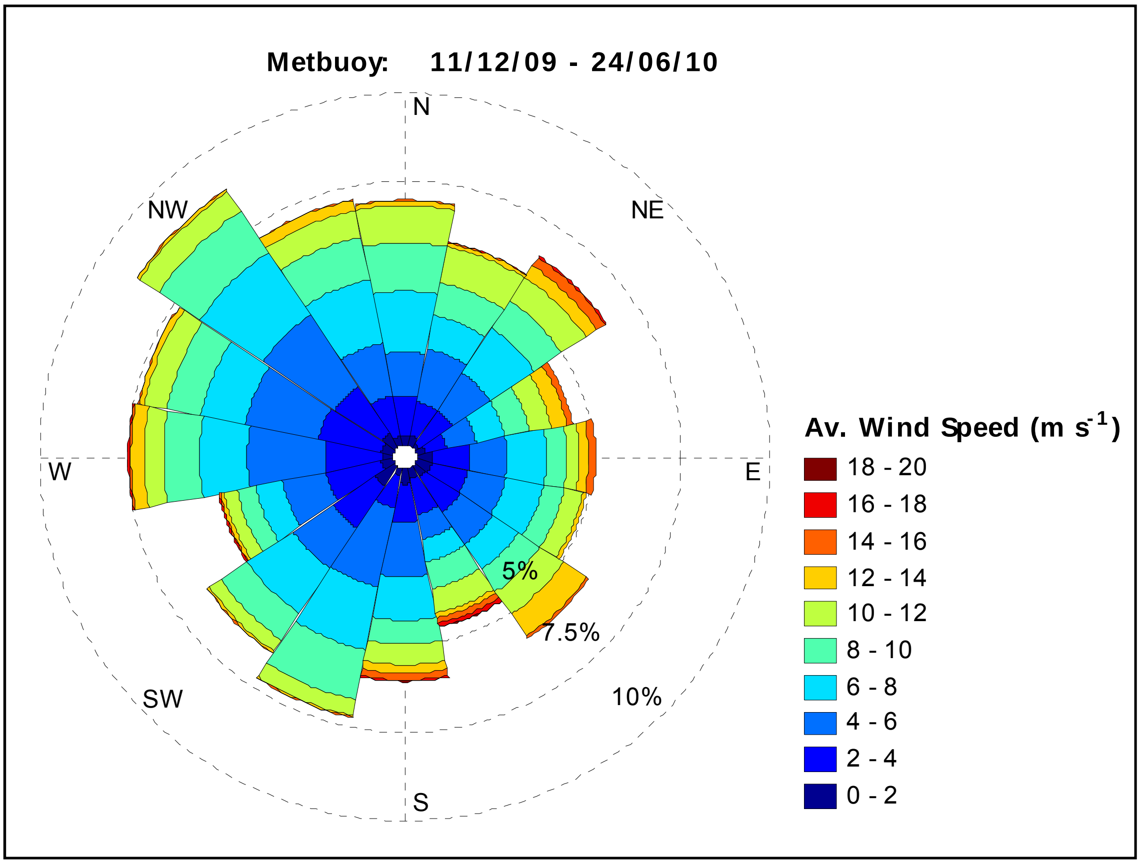


Figure 4-3 : Metbuoy: time series of wind speed (ms^{-1}) and direction (º)

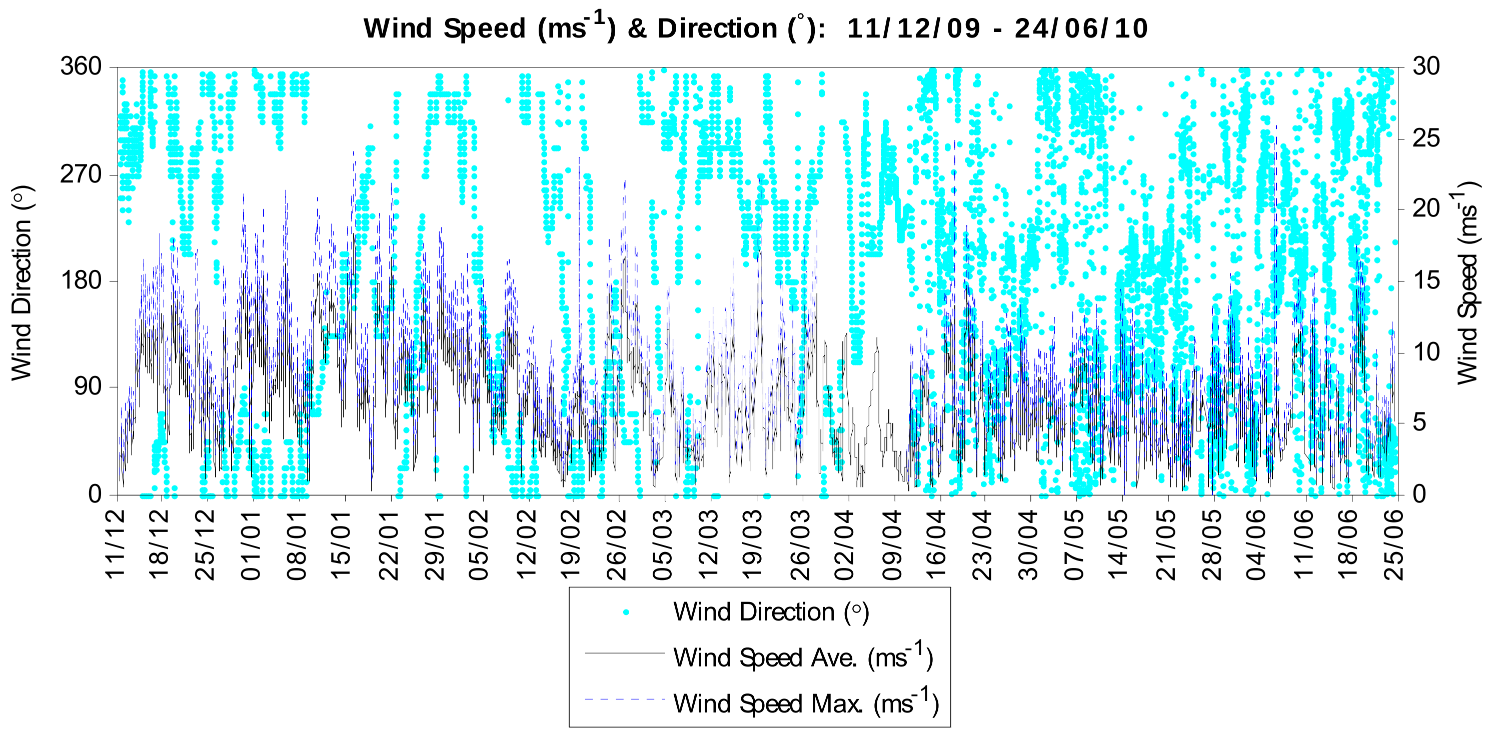
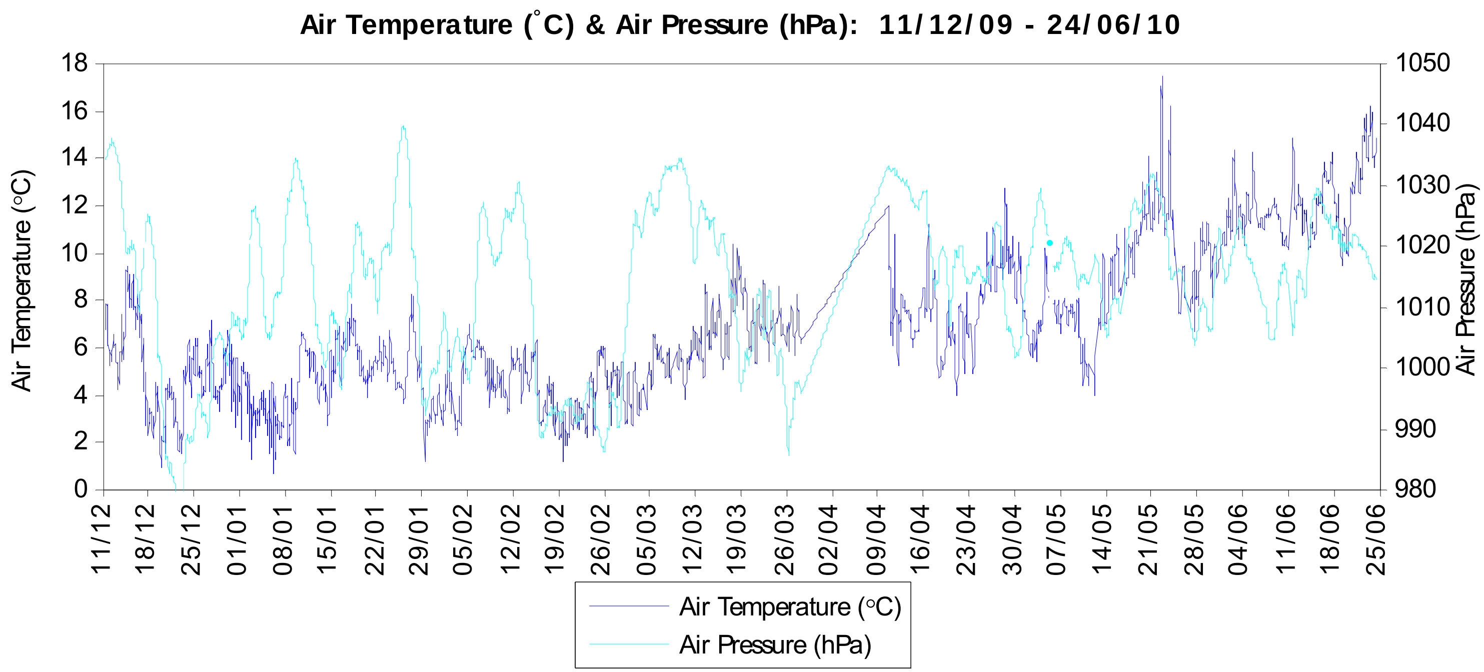


Figure 4-4 : Metbuoy: time series of air temperature and pressure



Note: the data dropouts around 28.3.10 (due to collision)

4.2 UK METEOROLOGICAL OFFICE DATA

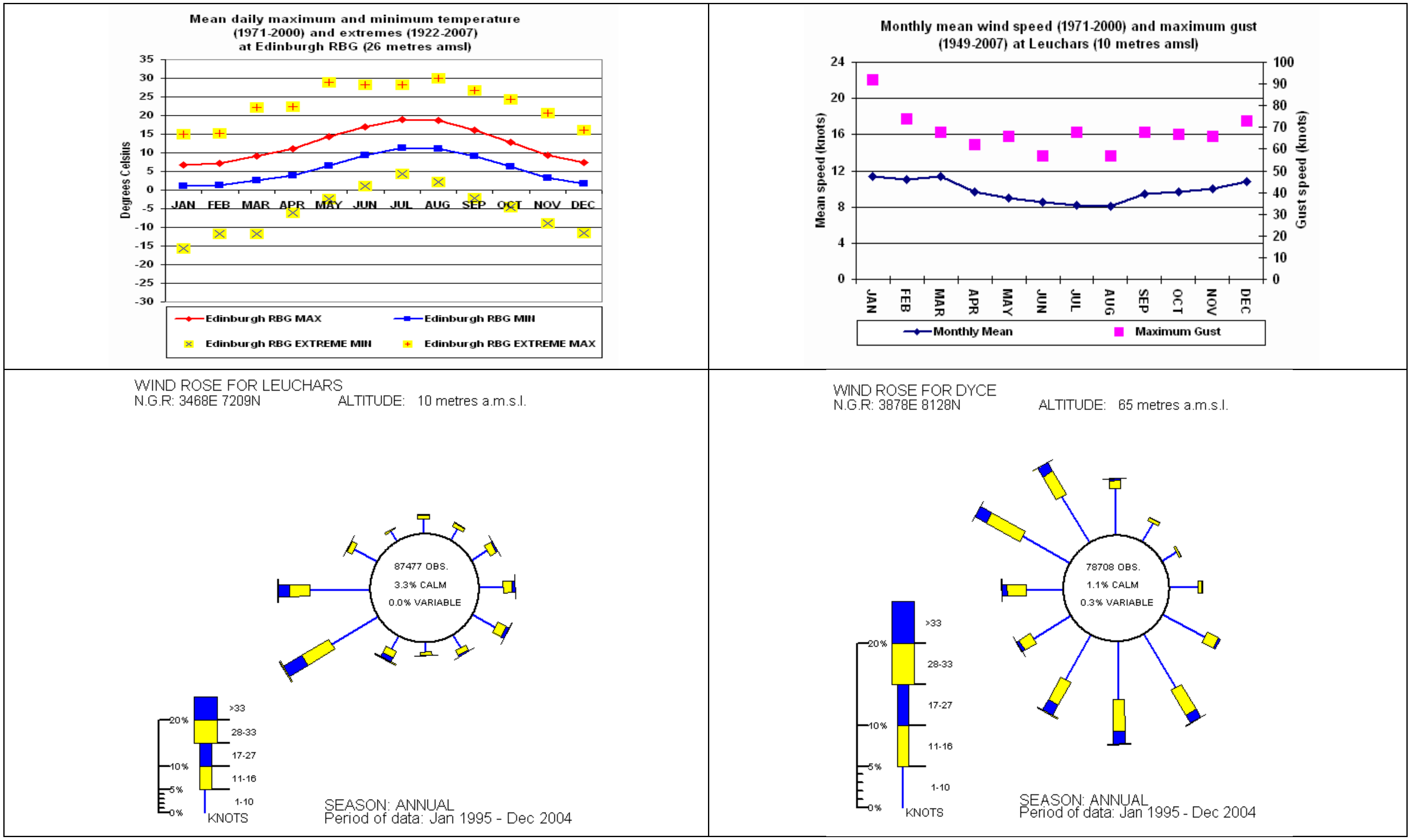
The UKMO has summaries of regional climate for the entire UK. The data for eastern Scotland[1] describes the main features of the climate of eastern Scotland, comprising the Borders, the Lothians, Falkirk, Clackmannanshire, Fife and the former regions of Tayside and Grampian, and is therefore of relevance to the present regional assessment. Figure 4-6 presents the summary data for the following: sunshine, rainfall, snow/sleet, temperature and wind. Only temperature and wind are considered here.

Mean annual temperatures over the Forth region are about 9 °C. January is the coldest month, with mean daily minimum temperatures varying from about 1.5°C. July or August are the warmest months. The variation in monthly mean speeds (average of a continuous record) and highest gusts ('instantaneous' speed averaged over about 3 seconds) at Leuchars (near to the Tay estuary mouth and therefore broadly representative of the outer Firths region) is shown in Figure 4-6. Whilst the mean speed does not vary widely seasonally, gusts are stronger and more powerful during winter months.

The direction of the wind is defined as the direction from which the wind is blowing. As Atlantic depressions pass the UK the wind typically starts to blow from the south or south west, but later comes from the west or north-west as the depression moves away. The range of directions between south and north-west accounts for the majority of occasions and the strongest winds nearly always blow from this range of directions, an observation broadly consistent with the (limited duration) monitoring data. Spring time tends to have a maximum frequency of winds from the north east. This seasonal effect is due to a build up of high pressure over Scandinavia. In Eastern Scotland, periods of very light or calm winds with no observable preferred direction vary from about less than 1% of the year on the coast to about 5% at sheltered places further inland. The annual wind rose for Leuchars is typical for the region, with an enhanced south-westerly wind direction through the year associated with a large-scale funnelling effect. In marked contrast, places further north, to the lee of the Grampian Mountains (and closer to the Angus coastal region), experience diminished south-westerlies as air is deflected by the high ground to the west. The annual wind rose presented in Figure 4-4 for Aberdeen airport (Dyce) is typical of this area. However, in all areas there tends to be a higher frequency of north to north-east winds in spring.

[1] http://www.metoffice.gov.uk/climate/uk/es/print.html

Figure 4-5 : Summary meteorological data for the outer Firths region from the Met Office regional database.

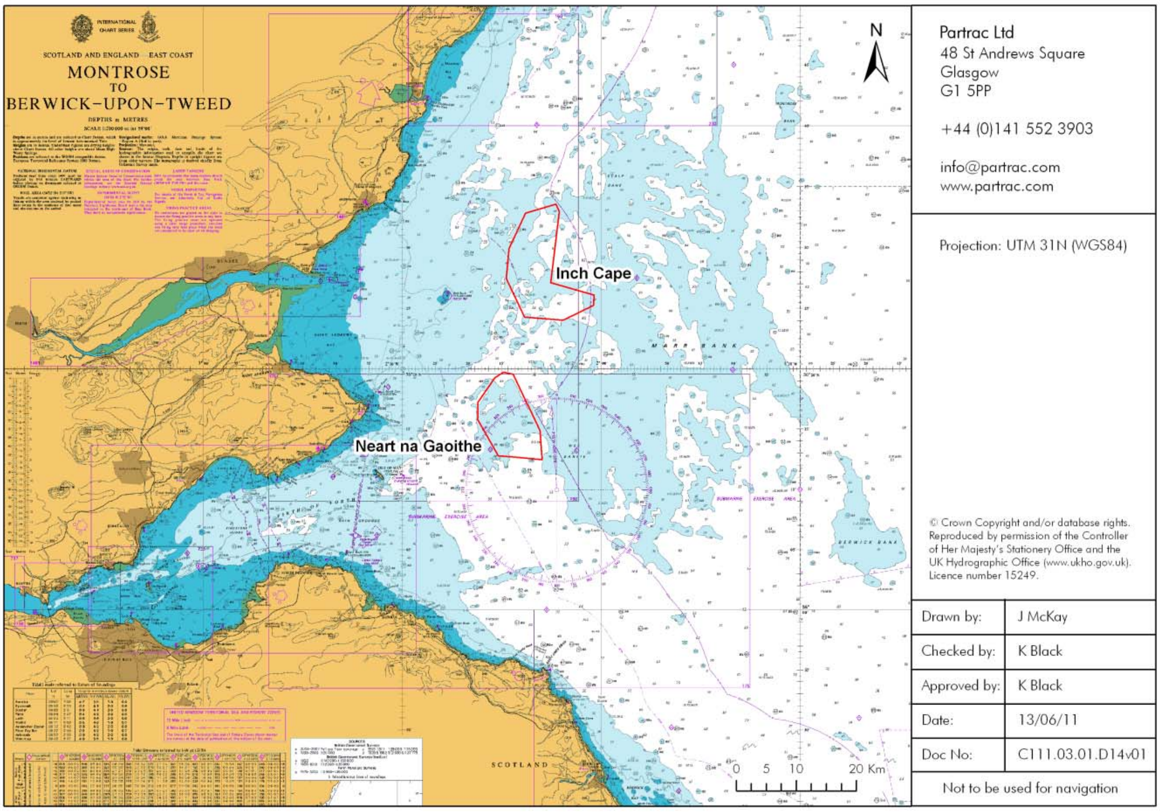


Source: http://www.metoffice.gov.uk/climate/uk/es/print.html.

5 BATHYMETRY

Gatliff *et al*., (1994) provide a thorough overview of the nearshore areas offshore of the Scottish-English northeast coast (Figure 5-1). The coastline comprises cliffs with intervening low-lying tracts and there are major embayments at the Firths of Forth and Tay. Offshore the seabed slopes to an extensive and generally flat platform. Water depths across the platform vary in the range of 60 m to 80 m below Chart Datum (CD) approximately. A number of banks are located within 50 km of the coast (Gatliff *et al*., 1994), notably the Marr Bank and the Scalp Bank offshore of the Firth of Forth. The Firths of Forth and Tay are major embayments, filled largely with Quaternary sediments and formed during the flooding of the Holocene Transgression. The seabed offshore Arbroath where the Inch Cape site is located extends in a broad gently sloping platform to ~50 m with local topographic highs and localised hollows reaching > 60 m. The seabed directly offshore the Fife Ness headland is the steepest within the Outer Firth of Forth region, descending to 40 m depth approximately 8 km offshore. The Neart na Gaoithe site is located on a slightly elevated section of the seabed, where depths range from 44 – 55 m. The deepest water is located along the eastern portion of the site.

Figure 5-1 : Map showing the general distribution of bathymetry along the northeastern seaboard of the British Isles.



Source UKHO.

6 GEOLOGY AND SURFICIAL SEDIMENT COVER

The solid geology of the region (Cairnbulg Point to St Abbs Head) is characterised by bedrock of Silurian, Devonian, Carboniferous, Permian and Triassic age. Locally much of the bedrock geology to the north of Fife Ness comprises mudstone, siltstone and sandstone, and in some areas marine limestone. To the south of Fife Ness, the geology is variable; comprising greywacke, shale, sandstone, limestone, basalt and dolerite. A number of vents of former volcanoes occur within the region (Ramsay & Brampton, 2000b), with the most notable located on the coastline to the southeast of St Andrews within the St Andrews to Craig Hartle SSSI (Site of Special Scientific Interest).

Much of the solid geology is overlain by more recent glacial and post-glacial deposits, comprising either till, pebbly glacio-marine muds, or sands with inter-bedded muds and silts (Stoker *et al*., 1985). Holmes (1977) and Holmes et al., (2004) outline the generalised vertical sequence of Quaternary sediment layers within the Outer Firth area and which is laterally extended northward into the Firth of Tay and up the Angus coastline (Table 6-1). Across the region the thickness of the Quaternary sediments i.e. the depth to the rock head (a factor which impacts on scour prediction and cable burial) is judged to be between ~10-20 m in the northern area and up to ~70 m in the area around the Neart na Gaoithe site. This is a generalised portrayal, and in some areas sub-surface formations (e.g. the Wee Bankie) or pre-Quaternary rock horizons outcrop.

Table 6-1 : Summary of approximate thicknesses of the major quaternary formations in the outer Firths area.

Approximate Depth of Unit Upper Layer (m)	Unit	Anticipated Soil Description
0 (surficial)	Holocene	SAND or gravelly sand
Typically 0- 5m, locally up to 20m	Quaternary (Forth Formation); includes Largo Bay (Fife) and St Andrews Bay members	Predominatly SAND with clay and slit layers
Typically 10- 20m	Quaternary (St Abbs Formation)	Soft to stiff, plastic weakly laminated MUDS to silty MUDS
35 – 45 m (variable)	Quaternary (Wee Bankie Formation)	Stiff to hard CLAY with interbeds of pebbly SAND and silty CLAY

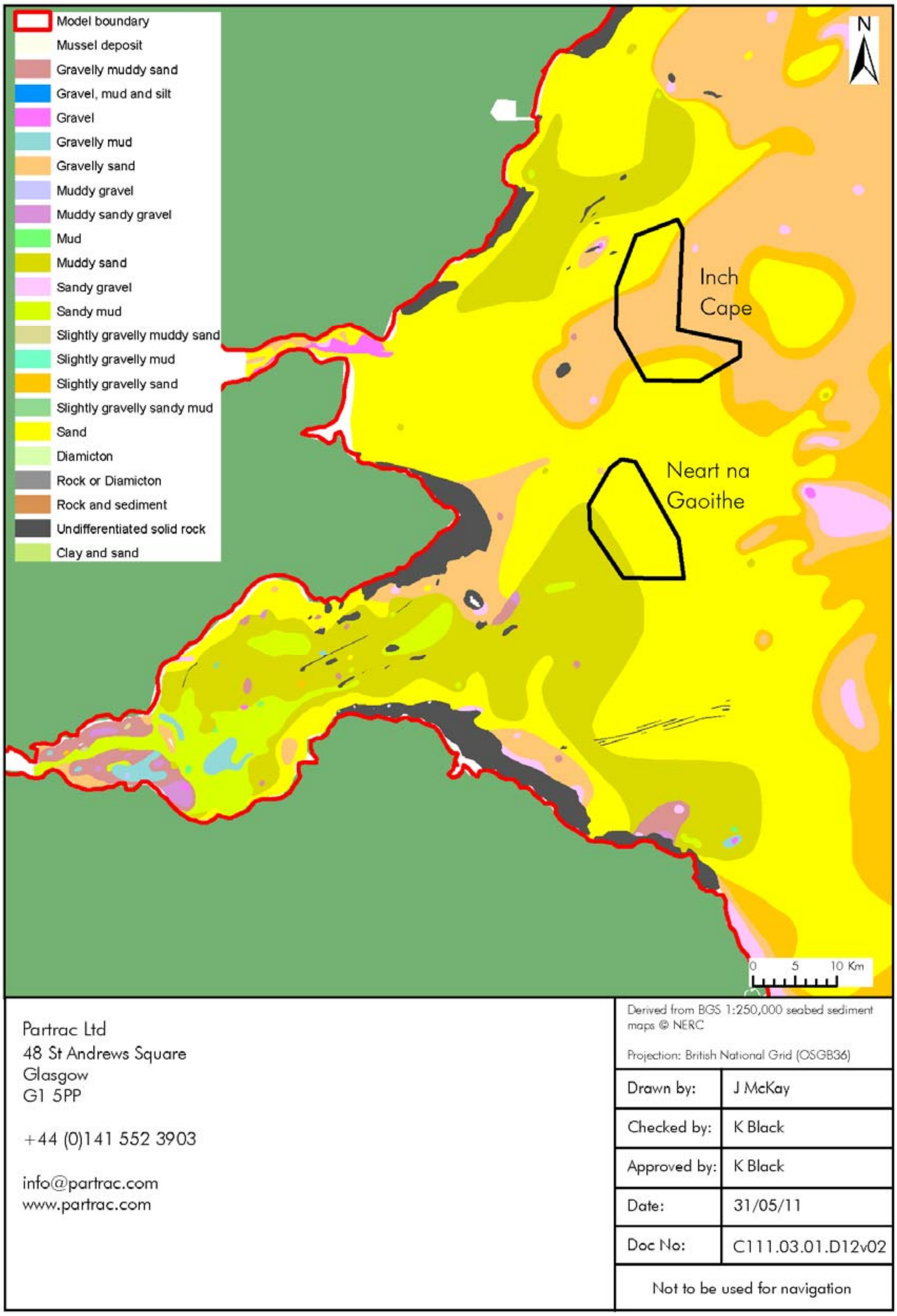
Source: Holmes (1977) and Holmes *et al*. (2004).

The surficial seabed sediments within the region comprise a veneer of unconsolidated terrigenous and biogenic deposits, generally < 1 m in thickness. Where they are absent, as occurs in some parts of the Inch Cape site boundary, the underlying Holocene and Pleistocene deposits, or bedrock, outcrop. The majority of contemporary seabed sediments consist of substrates that are more than 10,000 years old and have been reworked from sediment layers by tide and wave generated currents to form large sand and gravel areas (variously sand, muddy sand and gravelly sand), and may also form large-scale sandbanks, ridges and smaller sand waves or banks (DECC, 2009). Sand-sandy gravel sediment facies cover >80% of the region (Gatliff et al., 1994).

The sand material is generally fine to medium in grade (fine in areas of mud), but tends to be coarser in the vicinity of shallower regions (<~40 m) e.g. banks. Muddy sediments occur principally nearshore, for example in estuaries, where the sediment is supplied from the main rivers such as the Forth, and where they are able to accumulate in localised deeps or sheltered areas which are less frequently agitated by wave action. A centre of deposition for fine sediments is located off the Angus coast/Lunan Bay in ~20 m of water.

The distribution of surficial sediments is shown schematically in Figure 6-1.

Figure 6-1 : Distribution of surficial sediments along the northeastern seaboard of the British Isles, and within the outer regions of the Firths of Forth and Tay.



Source: BGS Seabed Sediments Tay-Forth 1:250,000 series (1986)/UK SeaMap (JNCC).

7 PHYSICAL OCEANOGRAPHY

7.1 GENERAL WATER CIRCULATION PATTERNS

The eastern seaboard of Scotland from St Abbs Head to Cairnbulg Point is characterised by astronomically forced tidal flows. The tide floods from the north as a result of the progression of the tidal wave up the Atlantic and around northern Scotland. Offshore Montrose the tidal currents are rectilinear and run parallel to the coast, with maximum spring tidal velocities ~17 km offshore of ~0.6 ms^{-1} (Admiralty Chart 1407). South of the Tay estuary the southerly directed flood tide forms a large clockwise eddy in St Andrews Bay that extends over Abertay Sands and into the main channel of the Tay (Charlton *et al*., 1975). Farther south the flood tide flows into the Firth of Forth, around Fife Ness. Across the mouth of the Firth, the flood tidal stream has a general east-southeast pattern, whilst the ebb tidal stream runs in a west-north-west direction. The currents are relatively low, with spring tides only reaching ~0.51 ms^{-1} in the Outer Firth of Forth (Ramsay and Brampton, 2000a). Within the Firth of Forth, near Rosyth, the spring currents are 0.7 - 1.1 ms^{-1} on the ebb, and 0.4 - 0.7 ms^{-1} on the flood. In general, the flood currents are stronger on the north side of the Firth and the ebb stronger on the southern shore. Consequently, there is a drift towards the west in the northern and central Firth, with an eastward flow along the southern shore. However, if the water near the northern coast becomes stratified in late winter to early spring, this can generate a seaward flow along the northern coastline as well (DECC, 2009). For additional information on water circulation in the Firth of Forth/Tay see Ramsay and Brampton (2000a).

7.2 TIDAL REGIME

7.2.1 Water Elevations

Tidal processes are characterised initially by, or related to, the nature of the tidal elevation signature. Down the northeastern seaboard of the British Isles, the tidal regime is semi-diurnal with a mean spring tide of ~4.5 m and a mean neap tide of ~2.2 m. During spring conditions a larger tidal volume is exchanged between high and low waters than during neaps for an equivalent tidal period (around 12.5 hours). This means that the rate of exchange of tidal water, and hence speed of flows, arriving (flood period) and departing (ebb period) in the Outer Forth and Tay estuaries is higher during springs than neaps. This feature of the tidal regime is important in influencing rates of, and net directions of, sediment transport. Table 4 presents primary tidal information for three ports around the periphery of the outer Firths region (Dunbar in the south, Leith in the Firth of Forth and Montrose, near to the Inch Cape development).

An analysis of the timings of high and low water for these ports shows the pattern of tidal elevations across the region due to the tidal progression. The time difference in high (or low) water between Montrose and Leith is ~38 minutes, which reflects the time it takes the tidal wave to progress from Montrose, southerly down the coast and across the outer Firth area and into the central Firth of Forth.

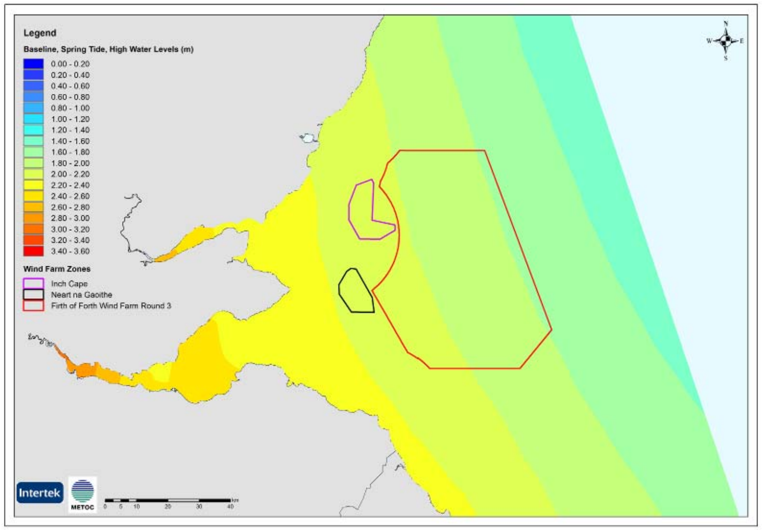
Table 7-1 : Summary tidal elevation data for Dunbar, Leith and Montrose

Tidal level (m)		Dunbar 56°00'N 02°31'W	Leith 55°59'N 03°11'W	Montrose 56°42'N 02°28'W
Highest Astronomical Tide	HAT	+3.10	+3.40	+2.95
Mean High Water Springs	MHWS	+2.50	+2.70	+2.25
Mean High Water Neaps	MHWN	+1.30	+1.50	+1.15
Mean Sea Level	MSL	+0.23	+0.30	+0.22
Mean Low Water Neaps	MLWN	-0.80	-0.90	-0.75
Mean Low Water Springs	MLWS	-1.90	-2.10	-1.85
Lowest Astronomical Tide	LAT	No data	-3.00	No data
CD to ODN	CD	+2.80	+2.90	+2.65
Tidal range				
Peak Range (HAT – LAT)		-	6.40	
Spring Range (MHWS - MLWS)		4.40	4.80	4.10
Neap Range (MHWN - MLWN)		2.10	2.40	1.90

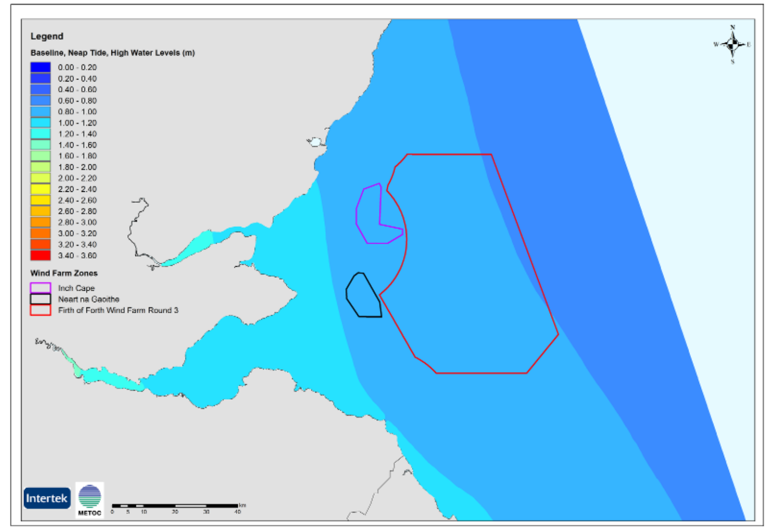
Note: (Metres above Ordnance Datum (Newlyn) (ODN)). Leith is the primary port. Source: UKHO/POL.

Water levels derived from the FTMS hydrodynamic model developed for the coastal processes assessment are presented in Figure 7-1. Mostly levels are uniform across each OWF site excepting spring tide, low water at Neart na Gaoithe.

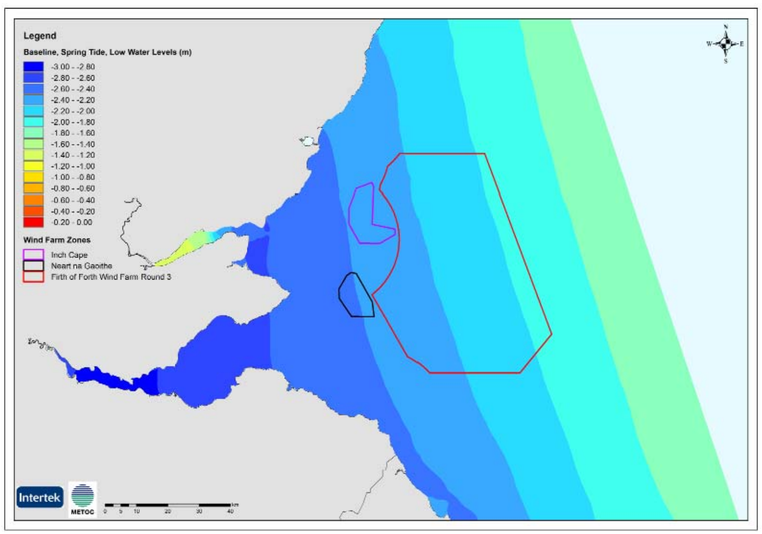
Figure 7-1 : Regional water levels across the outer Firths area from the FTMS hydrodynamic model



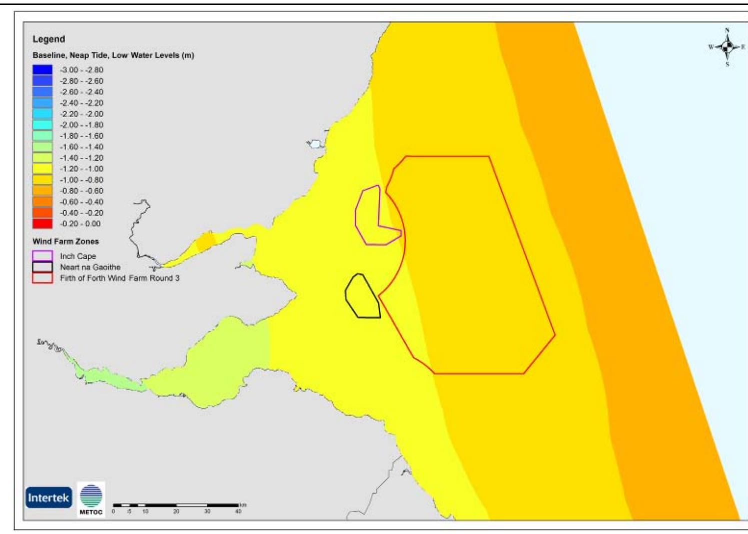
Spring tide, high water level (m)



Neap tide, high water level (m)



Spring tide, low water level (m)



Neap tide, low water level (m)

7.2.2 Non-Tidal Influences

Superimposed on the regular tidal behaviour, various random non-tidal effects may be present. Many of these non-tidal effects originate from meteorological influences. Persistent winds can generate wind-driven currents, set-up water levels and develop sea states that lead to wind-wave generation. Atmospheric pressure variations can also depress or raise the water surface to generate positive or negative surges, respectively.

Surges are formed by rapid changes in atmospheric pressure with an inverse relationship, i.e. low atmospheric pressure raises the water surface (positive surge) and high atmospheric pressure depresses the water surface (negative surge). These effects can cause water levels to fluctuate considerably above or below the predicted tidal level. Table 5 lists the top ten positive and negative surges obtained from existing tidal records at Leith (since 1981). Surges give rise to changes in water levels across large areas, and therefore changes in water level recorded at Leith will be found also in the outer Tay area and farther north and south, although the precise amplitudes may vary slightly.

Table 7-2 : Top ten positive and negative surges recorded at Leith port.

Date and Time	Surge (m)	Date and Time	Surge (m)
TOP 10 POSITIVE		TOP 10 NEGATIVE	
1989/02/14 02:00	1.38	1998/12/27 00:30	-1.36
1990/02/20 01:00	1.30	1996/11/06 08:30	-1.07
1998/11/10 02:00	1.26	1998/11/09 12:45	-0.87
1997/02/20 05:15	1.25	1996/03/12 07:00	-0.87
1993/02/20 22:30	1.15	1981/11/20 16:00	-0.85
1995/01/10 00:45	1.14	2006/10/26 17:30	-0.83
1991/12/19 20:00	1.13	1995/01/31 05:15	-0.80
1993/01/17 17:00	1.07	1993/01/24 00:15	-0.80
2006/01/11 07:15	1.06	1994/01/26 21:45	-0.79
2000/01/30 02:30	1.03	1994/01/29 12:30	-0.78

Source: POL 2011.

Over relatively short time periods (e.g. months) the tidal signal can be regarded as varying relative to a stationary level referred to as mean sea level (MSL). However, over longer time periods (e.g. several years) MSL varies in response to sea level rise and long period tidal trends (e.g. 18.6 year lunar nodal cycle). Hence, the baseline definition is non-stationary in situations when MSL also varies. The combination of an increasing mean sea level (as a function of sea level rise) and potentially increased storminess is an important issue for future coastal change within the Outer Forth and Tay Estuaries. Research for Department for Food, Rural and Environmental Affairs (Defra) by UK Climate Impacts Programme (UKCIP) suggests increases of up to 10% in the speeds and heights of extreme winds and waves on the coasts. The consequences in terms of coastal processes is likely to be most evident along the shorelines where much of the wave energy is finally dissipated leading to modified rates of littoral drift. The advancing position of mean high water on beaches will also lead to wave energy dissipation higher up on the foreshore with anticipated beach loss and scour in front of sea walls, or increased frequency of overtopping of coastal dunes or structures. Effects would also apply to offshore areas where the profile of sandbanks may reduce relative to local water depths introducing greater exposure to offshore waves (i.e. there is less wave shoaling and larger waves therefore can run up the shore). The impact of increased wave energy may have consequences for the sediment transport within the area.

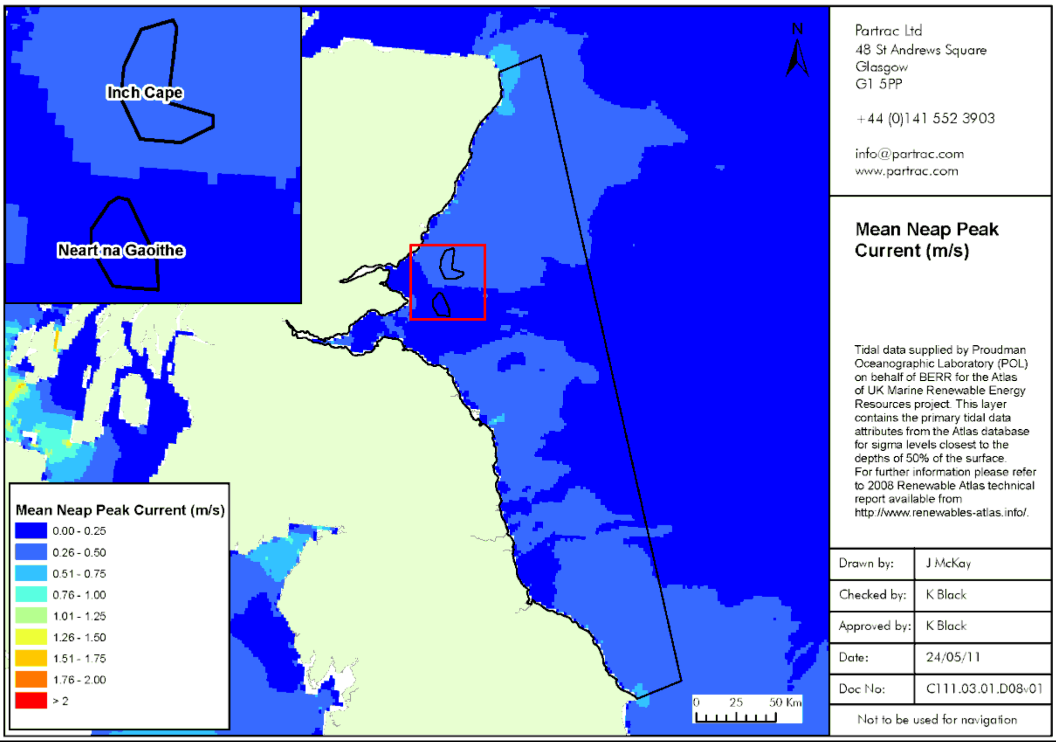
Future sea level rise results from the net effect of global change in sea level and the local change in land levels due to post-glacial rebound and subsidence. Based on Defra (2006) guidance the land in Scotland (which is rising) is assumed to have a rate of change of +0.8mm per year. The recommended value of relative sea level rise for flood and coastal defence planning for Scotland is 2.5 mm year-1 in sea level rise to 2025, 7.0 mm year^{-1} from 2025 to 2055 and then 10 mm year^{-1} from 2055 to 2085 (Defra, 2006). Table 7-1 shows that relative changes in sea-level are small in comparison to changes due to storm surges.

7.2.3 Tidal Currents

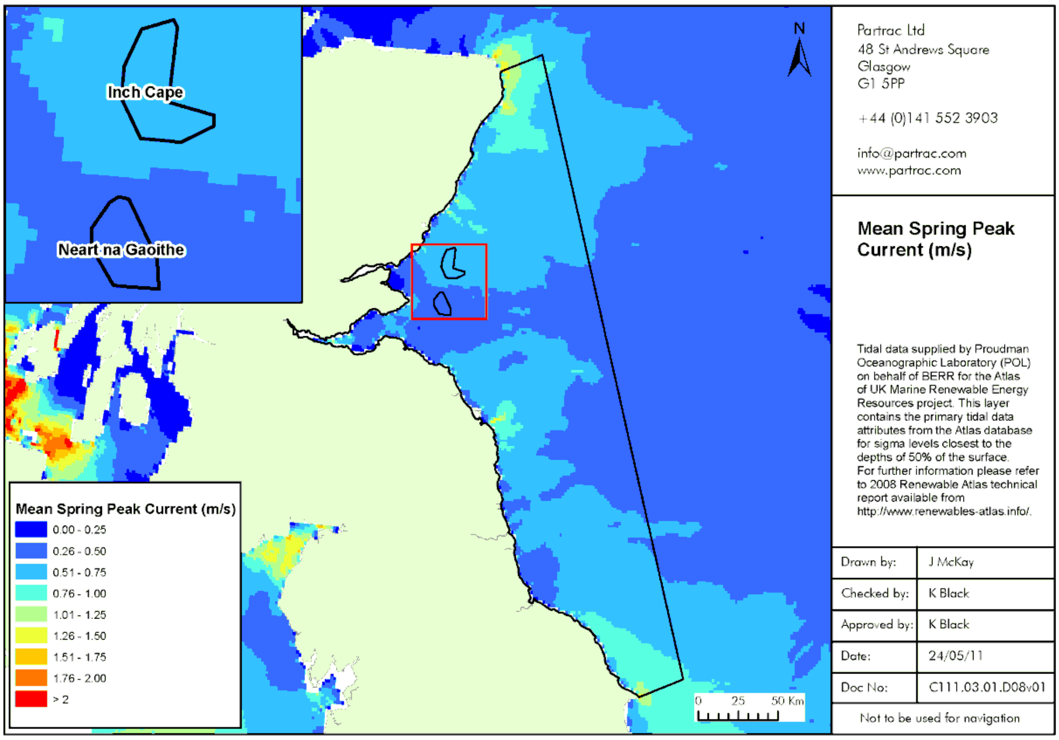
Synoptic, regional scale information on the magnitude of tidal currents is provided within the 2004/2007 DTI/BERR Atlas of Renewable Energy. Figure 7-2 shows plots of the peak spring and neap tide current magnitudes within the regional area. This indicate that on neaps the currents are largely similar (0.26 to 0.5 ms^{-1}) down the Aberdeenshire coast to round Montrose, except in embayments where they reduce; the Inch Cape development is within this area. The Neart na Gaoithe site is within a region of lower neap current velocity (< 0.25 ms^{-1}) which occupies the greater extent of the outer Firths region.

On spring tides, the spatial variability in current velocity is more noticeable, but the two sites are again in differing spatial velocity fields; peak spring tide velocities in the area of the Inch Cape site are 0.51 – 0.76 ms^{-1}. At Neart na Gaoithe these are lower and range 0.25 – 0.5 ms^{-1}.

Figure 7-2 : Synoptic plots of regional tidal current magnitudes for peak Neap (a) and peak Spring (b) tides.



a) Peak Neap tide current velocity (m s^{-1})

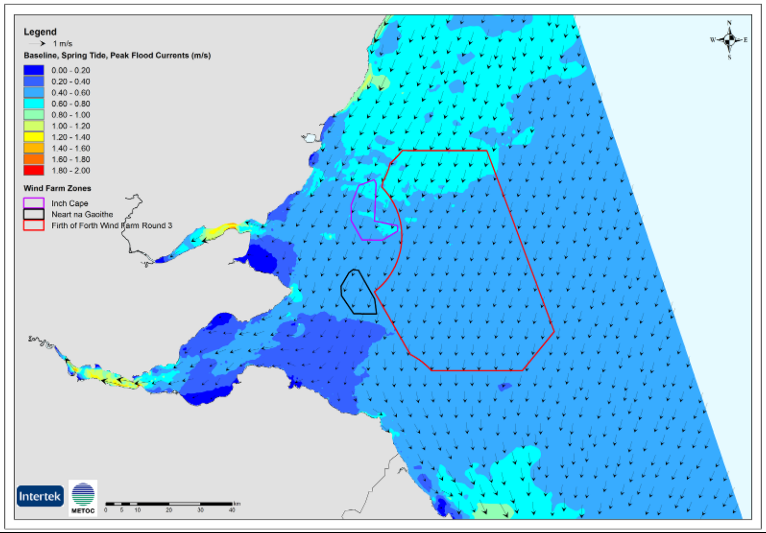


b) Peak Spring tide current velocity (m s^{-1})

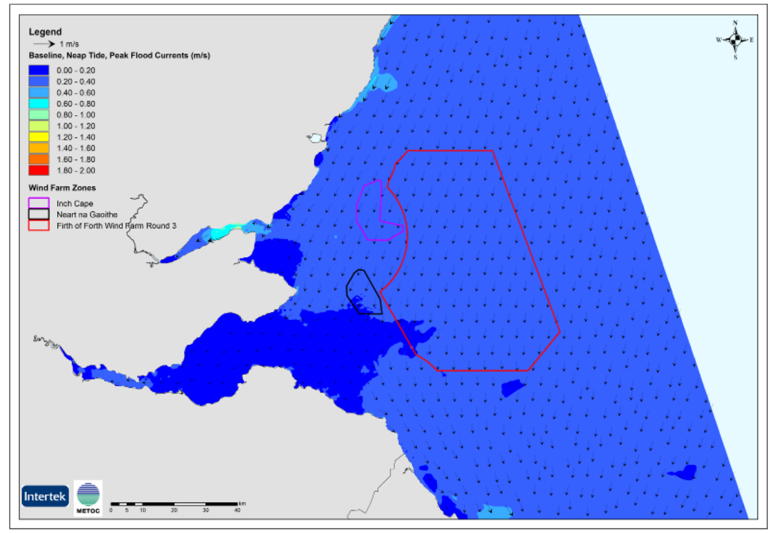
Source: Dti/BERR Atlas of Renewable Energy (2004/2007).

A more detailed impression of the velocity field including directional and magnitude vectors is available from the FTMS hydrodynamic model constructed for the coastal processes impact assessment (Figure 7-3). Largely the tidal current vectors are topographically controlled and run parallel to the coastline, except along the East Lothian coastline. In general terms currents are reasonably uniform across the Inch Cape and Neart na Gaoithe sites, except for at Inch Cape during peak springs, and there is good agreement between the Dti/BERR Atlas and the regional hydrodynamic model.

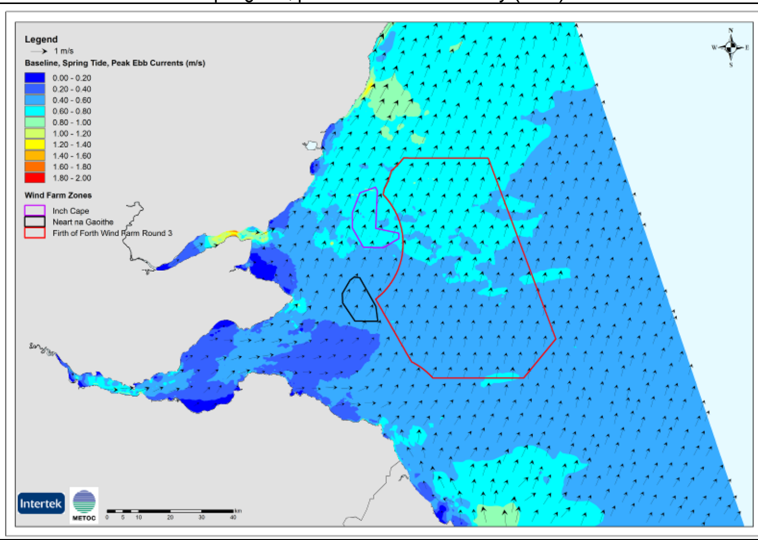
Figure 7-3 : Regional current velocity field across the outer Firths area from the FTMS hydrodynamic model



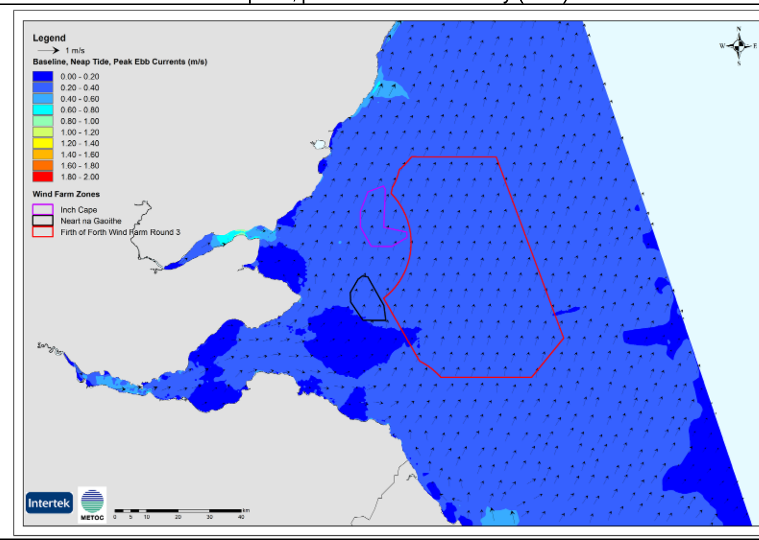
Spring tide, peak flood current velocity (m s^{-1})



Neap tide, peak flood current velocity (m s^{-1})



Spring tide, peak ebb current velocity (m s^{-1})



Neap tide, peak flood current velocity (m s^{-1})

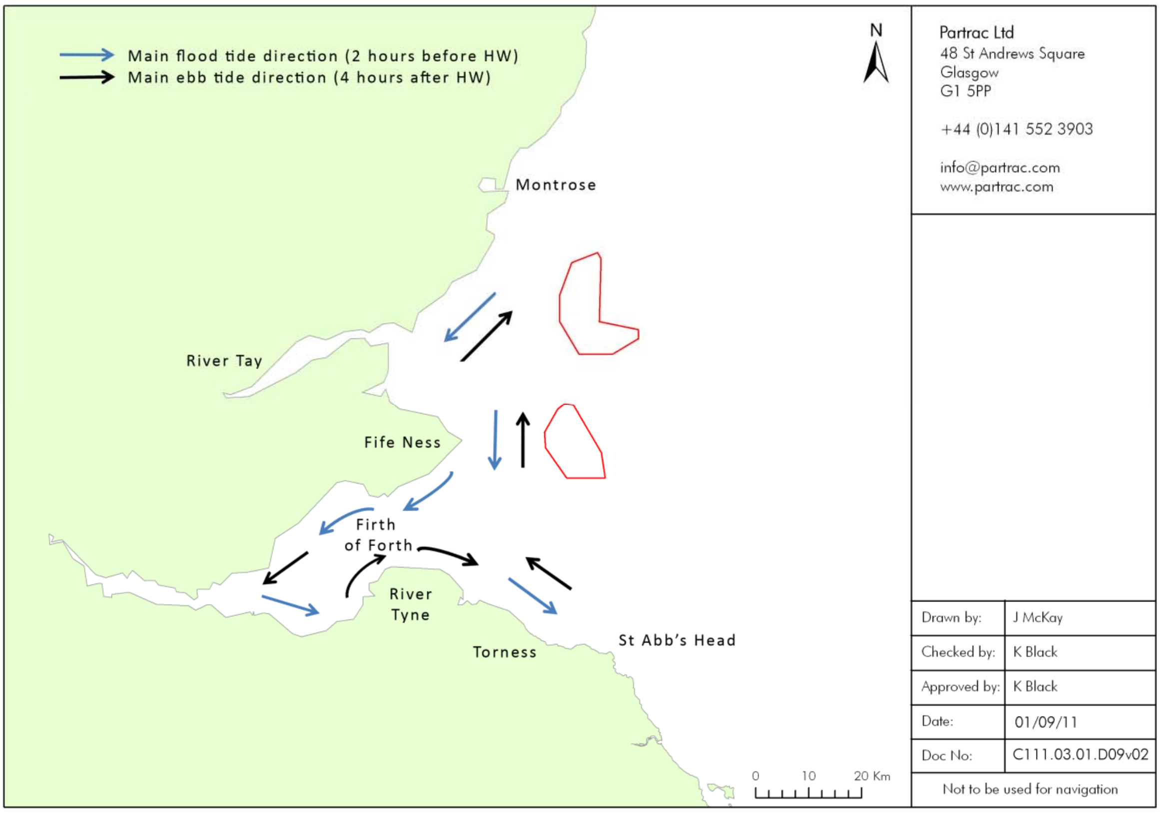
More specific data are available on Admiralty Charts and various short-term instrument deployments. The main archives holding measured data are the British Oceanographic Data Centre (BODC), but some data are also available within Scottish Environmental Protection Agency (SEPA) and Fisheries Research Service (FRS) archives. From the BODC archive there are numerous sites where current meters have been deployed in and around the Outer Firth of Forth. Table 7-3 provides details of the deployment locations closest to the proposed Inch Cape and Neart na Gaoithe OWF sites.

Table 7-3 : Details of BODC current measurement deployments

Series Reference	Latitude	Longitude	Sensor depth (m)	Record duration
Current meter data Inch Cape				
11697	56.4166° N	2.1666° W	44	17/08/1976 to 02/09/1976
11685	56.4166° N	2.1666° W	21	17/08/1976 to 02/09/1976
13286	56.3916° N	2.2029° W	45	28/10/1975 to 20/11/1975
Neart na Gaoithe				
431943	56.2715° N	2.3997° W	9	06/02/1993 to 01/04/1993
431955	56.2715° N	2.3997° W	46	06/02/1993 to 01/04/1993
432079	56.2715° N	2.3997° W	9	01/04/1993 to 09/05/1993
432080	56.2715° N	2.3997° W	46	01/04/1993 to 09/05/1993
432227	56.2715° N	2.3997° W	9	09/05/1993 to 03/07/1993
432239	56.2715° N	2.3997° W	46	09/05/1993 to 03/07/1993
432320	56.2715° N	2.3997° W	9	03/07/1993 to 11/09/1993
432332	56.2715° N	2.3997° W	46	03/07/1993 to 11/09/1993
432400	56.2715° N	2.3997° W	9	11/09/1993 to 20/10/1993
432412	56.2715° N	2.3997° W	46	11/09/1993 to 20/10/1993
432590	56.2722° N	2.3962° W	19	22/10/1993 to 11/12/1993
432608	56.2722° N	2.3962° W	56	22/10/1993 to 11/12/1993
Neart na Gaoithe and Inch Cape				
432368	56.3672° N	2.2963° W	9	04/07/1993 to 12/09/1993
432381	56.3672° N	2.2963° W	46	04/07/1993 to 12/09/1993
432528	56.3672° N	2.2963° W	9	12/09/1993 to 20/10/1993
432541	56.3672° N	2.2963° W	46	12/09/1993 to 20/10/1993
432565	56.3672° N	2.2963° W	9	20/10/1993 to 10/12/1993
432577	56.3672° N	2.2963° W	46	20/10/1993 to 10/12/1993
438862	56.3672° N	2.2963° W	9	20/10/1993 to 10/12/1993
432829	56.3657° N	2.3028° W	10	17/05/1994 to 04/06/1994
432830	56.3657° N	2.3028° W	43	17/05/1994 to 04/06/1994
432798	56.3657° N	2.3028° W	10	02/04/1994 to 17/05/1994
432805	56.3657° N	2.3028° W	43	02/04/1994 to 17/05/1994
432123	56.3658° N	2.3005° W	9	01/04/1993 to 09/05/1993
431992	56.3658° N	2.3005° W	46	06/02/1993 to 01/04/1993
432264	56.3665° N	2.3007° W	46	09/05/1993 to 03/07/1993
431980	56.3658° N	2.3005° W	9	06/02/1993 to 01/04/1993
432135	56.3658° N	2.3005° W	46	01/04/1993 to 09/05/1993

HR Wallingford (2009a) provides a detailed overview of these datasets. Figure 7-4 provides a graphic which illustrates the principal flood and ebb tidal current axes across the outer Firths region.

Figure 7-4 : Schematic of main flood and ebb tide directions in the outer Firths region.



Source: HR Wallingford (1998).

Tidal stream data are available on Admiralty Charts 175 and 190, which tabulate values at 11 sites from St Abb's Head to Montrose. These data provide an indicative value of surface flows through the tide and quoted relative to high water at Leith. Of these data there are two tidal stream locations ('A' and 'B') which are in the vicinity of the Neart na Gaoithe site, and two inshore of the Inch Cape site (off the Angus coast) ('D' and 'E'). The variation in flow speed and direction at these locations through a tidal cycle is summarised in Tables 7-4 and 7-5. The data indicate that peak flows on mean spring tides within the area are around 0.31 ms-1 in the vicinity of the Neart na Gaoithe site but are much stronger (approaching ~1 ms-1) in the vicinity of the Inch Cape site. Of interest there appears to be no strong tidal asymmetry within Neart na Gaoithe site and none observed at the offshore site at Inch Cape (site 'A'). However, data from site B at Inch Cape would indicate an ebb dominance to the flow magnitudes.

Table 7-4 : Tidal stream data (surface flow magnitude and direction) from UKHO Chart 175 sites 'D' and 'E'.

Hours		Tidal stream - (D) 56°16.9'N, 02°23.4'W			Tidal stream - (E) 56°13.3'N, 02°16.6'W		
		Direction (°N)	Spring (m s^{-1})	Neap (m s^{-1})	Direction (°N)	Spring (m s^{-1})	Neap (m s^{-1})
Before High Water	-6	344	0.306	0.153	348	0.306	0.153
	-5	315	0.153	0.102	340	0.306	0.153
	-4	221	0.153	0.102	317	0.255	0.102
	-3	236	0.204	0.102	245	0.153	0.051
	-2	201	0.255	0.102	189	0.255	0.102
	-1	192	0.255	0.102	176	0.255	0.153
High Water	0	162	0.204	0.102	164	0.306	0.153
After High Water	1	149	0.204	0.102	162	0.255	0.102
	2	103	0.153	0.051	166	0.153	0.102
	3	032	0.255	0.102	120	0.051	0.051
	4	021	0.255	0.153	024	0.255	0.102
	5	010	0.306	0.153	010	0.306	0.153
	6	348	0.306	0.153	001	0.306	0.153

Source: UKHO, 1993. HW relative to Leith.

Table 7-5 : Tidal stream data (surface flow magnitude and direction) from UKHO Chart 190 sites 'A' and 'B'.

Hours		Tidal stream - (A) 56°40' 09"N, 02° 09' 69"W			Tidal stream - (B) 56°27' 49'N, 02°14' 59"W		
		Direction (°N)	Spring (m s^{-1})	Neap (m s^{-1})	Direction (°N)	Spring (m s^{-1})	Neap (m s^{-1})
Before High Water	-6	016	0.408	0.204	101	0.255	0.153
	-5	020	0.153	0.051	287	0.714	0.357
	-4	184	0.204	0.153	283	0.867	0.459
	-3	194	0.408	0.204	269	0.867	0.459
	-2	194	0.510	0.255	266	0.765	0.408
	-1	191	0.612	0.306	267	0.612	0.306
High Water	0	194	0.51	0.225	277	0.357	0.153
After High Water	1	208	0.204	0.102	063	0.153	0.102
	2	348	0.153	0.051	098	0.765	0.408
	3	009	0.102	0.153	100	1.071	0.561
	4	014	0.51	0.255	097	1.02	0.51
	5	016	0.612	0.306	096	0.918	0.459
	6	018	0.459	0.204	100	0.612	0.306

Source: UKHO, 1993. HW relative to Leith.

7.2.4 Oceanographic Monitoring Data

Data on (depth-averaged) tidal current magnitudes were collected by the Forth and Tay Offshore Wind Developers Group (FTOWDG) consortium. Four sites were instrumented, although only two of these are being taken forward for development. The data are presented in Table 7-6 and reveal generally highly similar mean and peak current velocities across the region, although currents are slightly higher at Inch Cape.

Table 7-6 : Summary of tidal current data collected during a regional oceanographic monitoring campaign

	SITE			
PARAMETER	Forth Array	Neart na Gaoithe	Inch Cape	North Offshore
Maximum Current Velocity ($m\ s^{-1}$)	1.1	1.3	1.3	1.3
Tidal Mean Current Velocity ($m\ s^{-1}$)	0.2	0.2	0.3	0.2
Principal Current Axis (°)	NW / SSE	N / S-SSW	NNE / SSW	N-NNE / SSW

7.2.5 Non-Tidal Currents

In addition to the tidally driven currents, the flow regime can be influenced by density driven currents arising from the mixing process between the freshwater inputs and the sea, by wind stress, storm surges and by waves. In general, the significance of such non-tidal effects is more likely to be evident during periods of neap tides when the tidal signal is at its weakest.

Density-driven currents arise because of differences in salinity and/or temperature in two interconnected bodies of water. HR Wallingford (2009a) undertook an analysis of the relative volumes of freshwater discharged from the two largest river systems (the Forth and Tay rivers) in relation to the tidal prism and concluded that localised freshwater input volumes to the coastal region were negligible for each site. Freshwater volumes are presented in Table 8-2 (section 8) Furthermore, the Inch Cape and Neart na Gaoithe development sites can be regarded as being well-mixed by tidal and wave-induced currents through the year. Therefore, the effect on the overall flow patterns from varying density driven currents is not deemed significant for the outer Firth region.

7.3 Wave Regime

7.3.1 Regional Wave Climate

A wave climate results from the transfer of wind energy to create sea-states and the propagation of such energy across the water surface by wave motion. The amount of wind energy transfer and wind-wave development is a function of the available fetch distance across which the wind blows, wind speed, wind duration and the original state of the sea. The longer the fetch distance, the greater the potential there is for the wind to interact with the water surface and generate waves. In shallower water, water depth is an additional limiting factor on the size of waves.

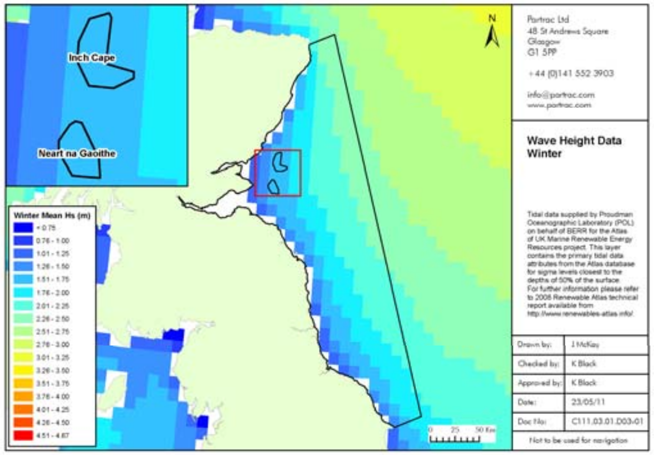
The wave regime in the proposed development area can be regarded as the combination of swell waves moving into the area (having been generated remotely from the area) and locally generated wind-waves. The wind farm site is open to easterly offshore waves that are generated within the North Sea. However, for locally generated waves the prevailing winds come from south-westerly sectors and will be fetch limited, and therefore there is a natural limit to the sizes wave can attain from this direction.

Wave data for the outer Firths region are limited, both in terms of number of available sites and duration of observations. The data sources found for the area presently includes the following:

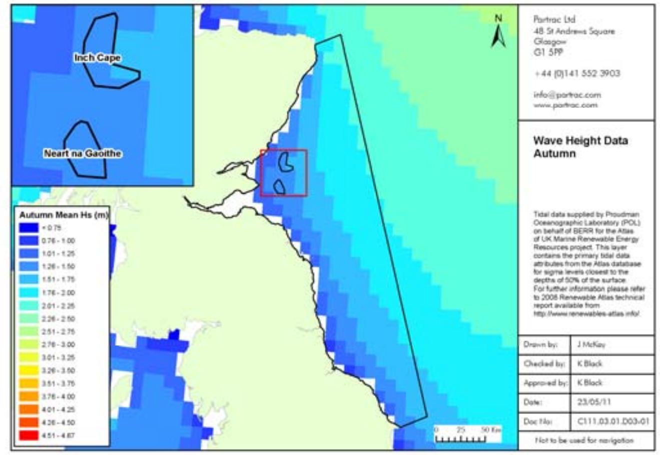
- FTOWDG oceanographic monitoring campaign (real data);
- Cefas Wavenet data buoy (real data);
- Model output from the detailed FTMS spectral wave model;
- The 2004/2007 Dti/BERR Atlas of Renewable Energy;
- Predicted deep water wave conditions from Met Office from:
    - European Wave Model.
    - UK Wave Model.
- Non-directional wave information from BODC for period 1969 to 1970 at: 56° 18.5'N, 2° 32'W; and
- Various modelling studies (Offshore Technology Report, 2001; HR Wallingford; 1998).

Synoptic, regional scale information on the magnitude of waves (i.e. wave height) is provided within the Dti/BERR (2007) Atlas of Renewable Energy. This is a model created using 3-7 years of archive tide, wind and wave data provided by the Proudman Oceanographic Laboratory (POL) High Resolution Continental Model (HRCS) (for tidal) and by the Met Office UK Waters Wave Model (for offshore waves). The Atlas comprises the best archive of oceanographic data available at present. Figure 7-5 shows plots of the inshore and offshore wave significant through the seasons. These indicate that wave energy across the outer Firths region is seasonally variable, with highest waves occurring during winter months. Wave heights range from < 0.75 m during summer months to over 1.7 m during winter months. At this scale, both sites appear within the same wave height banding i.e. they are equally exposed, although during spring and autumn there would appear to be spatial variability in wave height across the Inch Cape site.

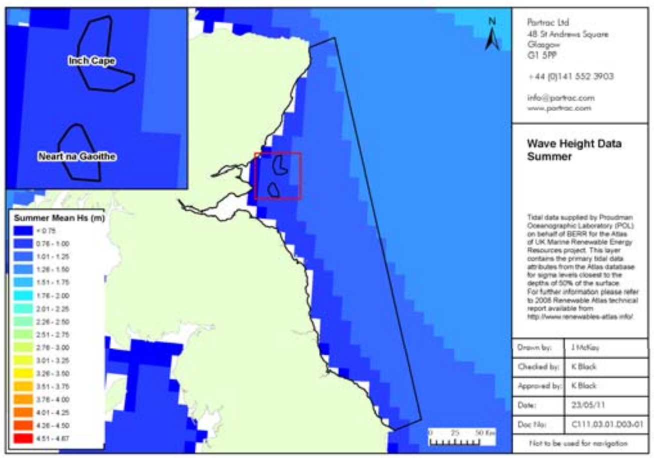
Figure 7-5 : Synoptic plots of regional significant wave height (Hs) by season.



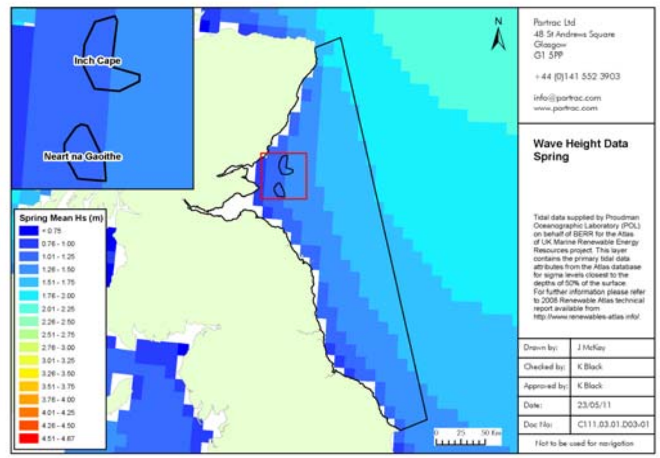
a) Winter; Hs=1.51 – 1.75 m



b) Autumn; Hs=1.26 – 1.50 m



c) Summer; Hs<0.75 m



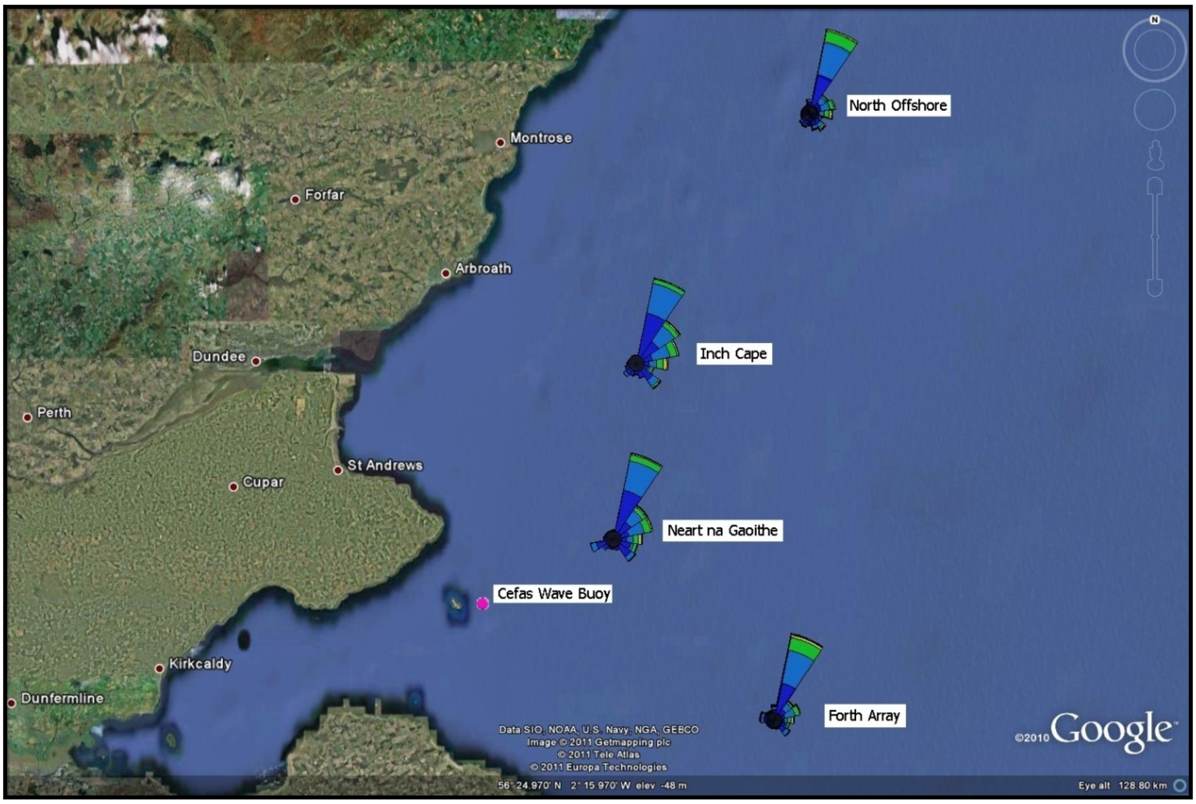
d) Spring; Hs=0.76 – 1.0 m Neart na Gaoithe; Hs=0.76 – 1.25 m

Source: DTI/BERR Atlas of Renewable Energy (2004/2007).

Additional data are available from a number of other modelling studies. HR Wallingford (1998) report that offshore wave conditions are experienced from around 340°N through to 200°N. On average, 35% of the wave conditions come from the sector 20°N to 60°N, with significant wave heights of over 4 m being experienced from any direction in the easterly sector, but most commonly occurring from between 0°N to 120°N, due to a greater prevalence for extreme wind conditions from the north east rather than the south east. Swell wave conditions are dominated by waves generated from between 20°N and 60°N, with approximately 60% of swell conditions experienced from this sector. Swell conditions from the other directions is limited due to short fetch lengths or insufficient wind duration.

Synoptic data, collected over the period 07/12/09 to 26/06 – 12/07/10 from the oceanographic monitoring undertaken at Inch Cape, Neart na Gaoithe, Forth Array (now defunct) and North Offshore (now defunct) shows the modal wave directions across the outer Firth region (Figure 7-6) and this generally supports the above assessment. The predominant direction is centred on 22.5^{o} across the entire area, and waves (swell) up to 5 m Hm0, with periods in excess generally of 7 s, are recorded. These occur mostly during winter storm periods. The most common waves, however, range in height up to 2 m. Minor components corresponding to locally generated waves are seen from the SW and SE directions. Table 7-7 presents summary statistical data for oceanographic parameters for each of the sites for the entire monitoring period.

Figure 7-6 : Wave direction and magnitude in the outer Firths region.



Source: FTOWDG oceanographic monitoring campaign. Data collected over the period 7 - 10/12/09 to 26/06 – 12/07/10. Also shown is the location of the Cefas WaveNET buoy.

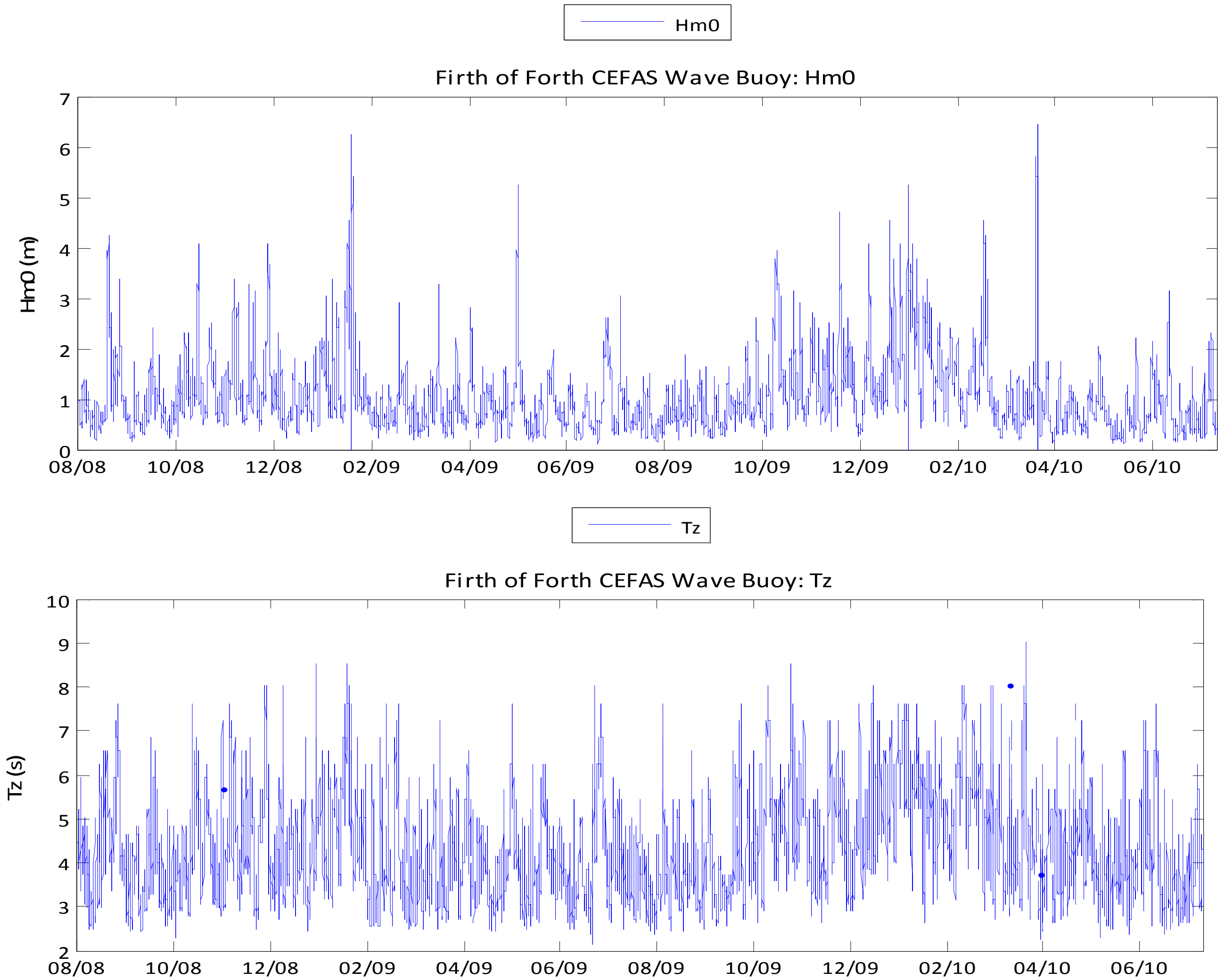
Table 7-7 : Summary statistics for key oceanographic parameters for each of the sites for the entire monitoring period.

	SITE			
PARAMETER	Forth Array	Neart na Gaoithe	Inch Cape	North Offshore
Maximum Significant Wave Height – Hs_{max} (m)	6.5	6.2	5.9	6.5
Mean Significant Wave Height – Hs_{ave} (m)	1.4	1.3	1.3	1.5
Modal Peak Direction Dir_p (º)	19.2	26.2	26.2	19.2
Modal Wave Period – Tp (s)	10	9	9	9
Maximum Wave Period – Tp_{max} (s)	18.1	16.6	15.3	16.6

Long-term wave data is also available from the Cefas Wavenet buoy in the Forth of Firth. This is located at 56°11'.33 N and 002°30'.24 W (to the west of the Neart na Gaoithe buoy; Figure 7-6) in ~65 m of water. This buoy is a relatively new deployment and data are available from 19th August 2008 to 11th March 2011. Figures 7-7 and 7-8 show these data.

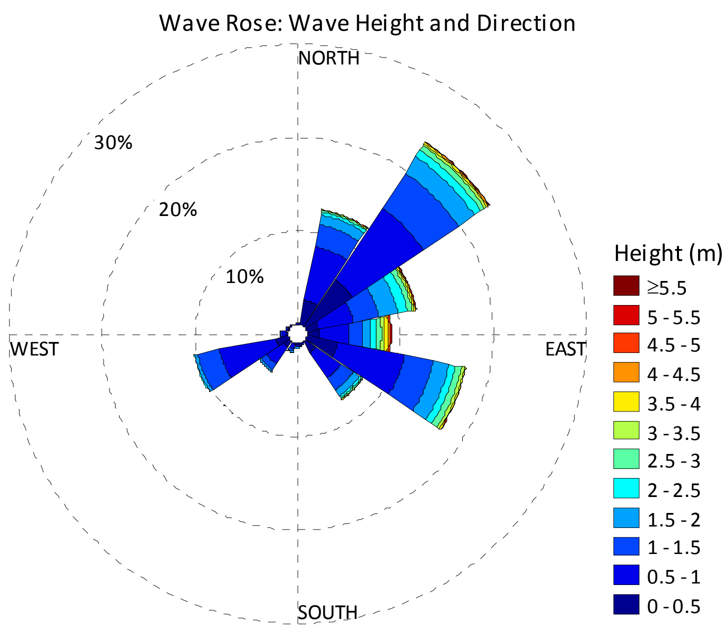
These data largely confirm the observations from both modelling and the regional oceanographic monitoring campaign. The dominant wave direction is from the NE (Figure 7-8) (compare this with the plots in Figure 7-6) but these data reveal also waves from SE and WSW/SW in relatively greater proportion in relation to the synoptic monitoring. The biggest waves (> 5 m) come from the east. Wave heights centred upon ~ 0.8 m occur through the summer months, increasing to ~2 to 3 m through winter months, with intermittently higher waves approaching 4 to 6 m during more energetic periods. Wave periods range from ~2.5 to 8 s; typical summertime periods are ~2.5 to 4.5 s whereas typical periods are slightly higher during winter (~4 to 8 s) in response to incoming swell.

Figure 7-7 : Significant wave height (Hs /Hm0 top panel) and period (Tz, lower panel) from the Cefas WaveNet buoy



Note: Cefas WaveNet buoy located at 56°11'.33 N and 002°30'.24 W, and data presented for the period 19th August 2008 to 11th March 2011. Source: Cefas

Figure 7-8 : Wave direction and magnitude (plus frequency of occurrence by direction statistics) from the Cefas WaveNet buoy

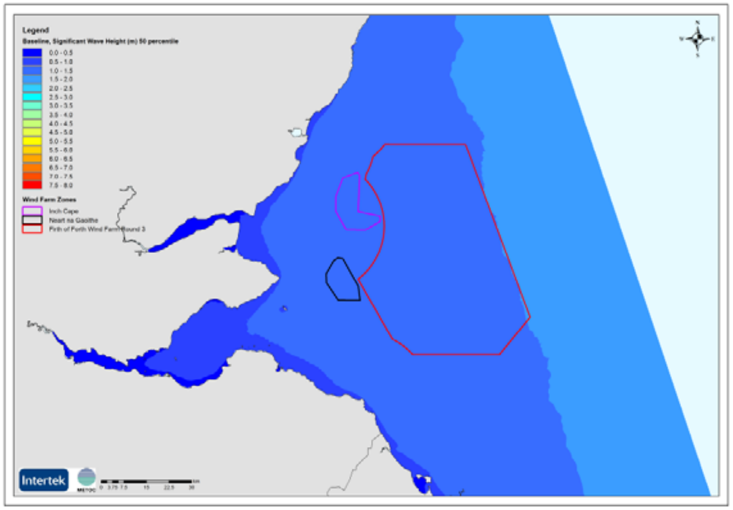


Direction	Frequency (%)
E	9.09
ENE	12.02
NE	23.75
NNE	12.58
N	0.12
NNW	0.05
NW	0.15
NWN	0.31
W	0.90
WSW	10.31
SW	3.92
SSW	1.07
S	0.51
SSE	0.34
SE	7.48
ESE	17.43

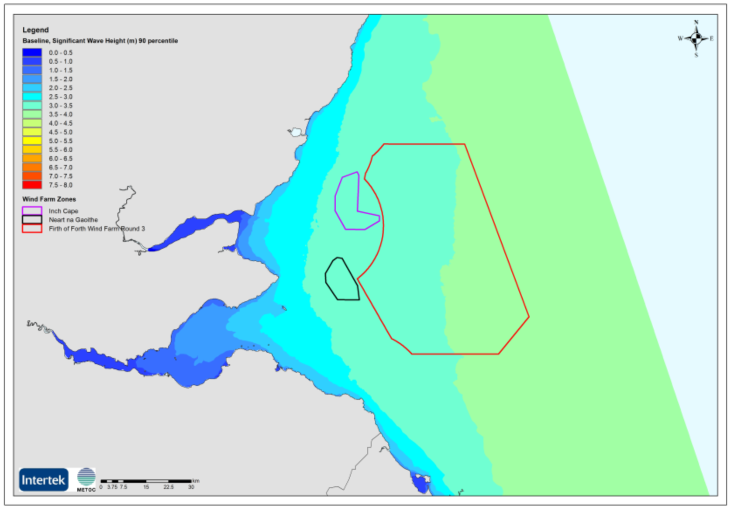
Note: Cefas WaveNet buoy located at 56°11'.33 N and 002°30'.24 W) and data presented covers the period 19th August 2008 to 11th March 2011. Source: Cefas.

A more detailed impression of the wave field including significant wave height and peak wave period is available from the FTMS spectral wave model constructed for the coastal processes impact assessment (Figures 7-9 and 7-10). These demonstrate very uniform wave heights and periods across both OWF sites under all conditions, although the extreme wave heights (99%ile) at the Inch Cape site are predicted to be slightly greater than at the Neart na Gaoithe site.

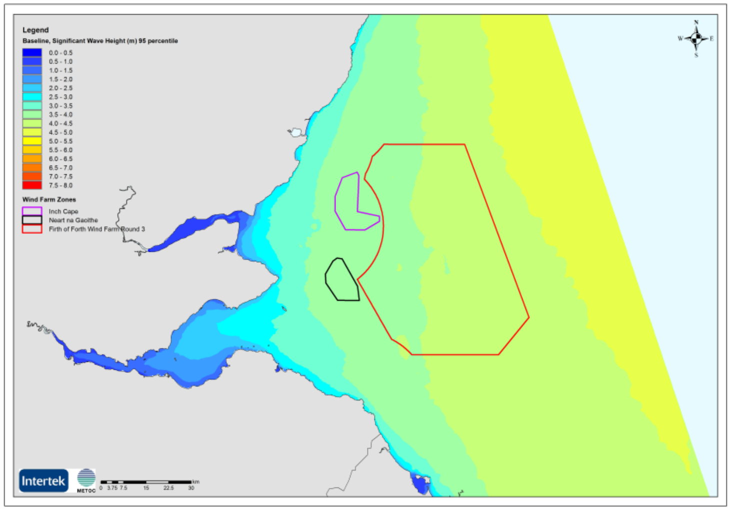
Figure 7-9. Regional significant wave height (m) across the outer Firths area from the FTMS spectral wave model



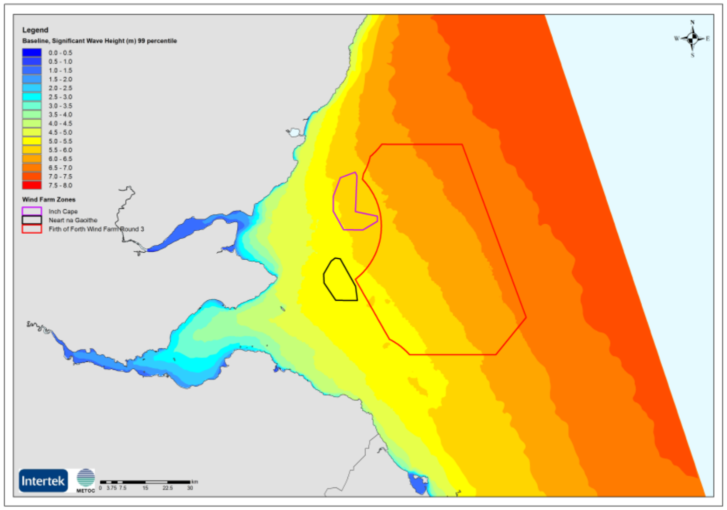
50-percentile (10-year) significant wave height (m)



90-percentile (10-year) significant wave height (m)

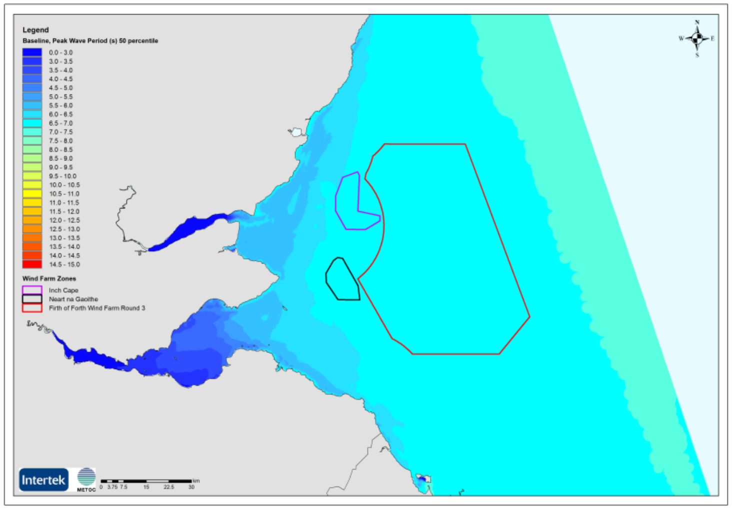


95-percentile (10-year) significant wave height (m)

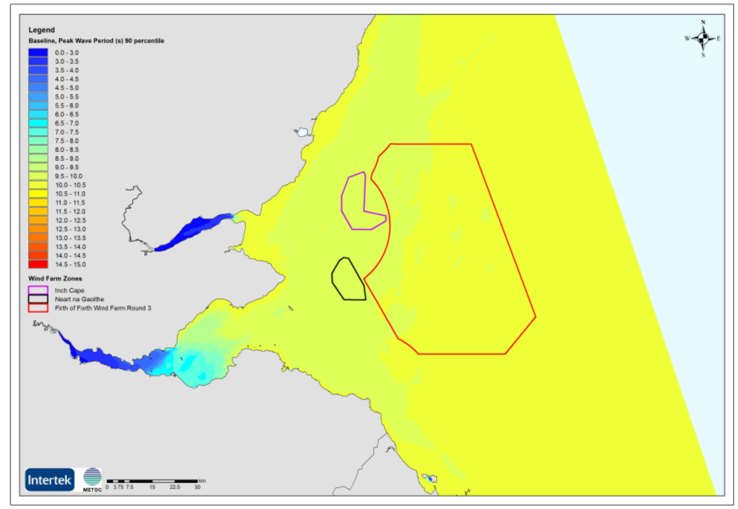


99-percentile (10-year) significant wave height (m)

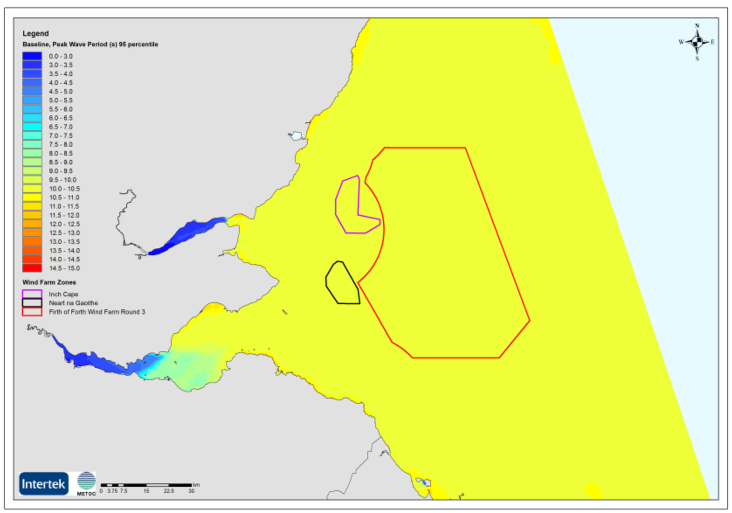
Figure 7-10. Regional peak wave period (s) across the outer Firths area from the FTMS spectral wave model



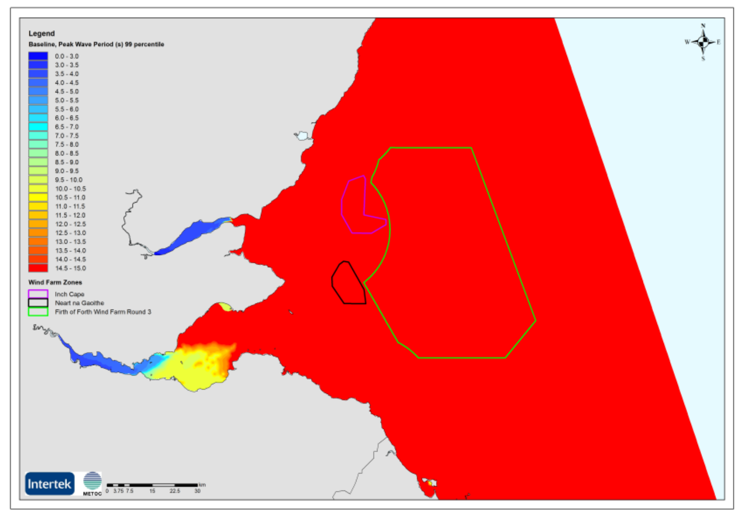
50-percentile (10-year) peak wave period (s)



90-percentile (10-year) peak wave period (s)



95-percentile (10-year) peak wave period (s)



99-percentile (10-year) peak wave period (s)m)

7.3.2 Extreme Waves

Marine environments are susceptible to the highly infrequent occurrence of extreme conditions. Modelling of wind and waves (Offshore Technology Report, 2001) showed that waves remain under 4.5 m for 99% of the time in the outer Firths region, which is generally consistent with the data from all the regional oceanographic monitoring (including Cefas data). Extreme waves may thus be considered as waves over ~ 4 - 5 m in height.

The offshore wave climate, both total sea (swell and wind generated) and significant wave height for return periods of 1-100 years, have been reported on by Ramsay & Brampton (2000a and b) for coastal cells to the north and south of Fife Ness respectively (Cairnbulg Point to St Abbs Head), and by Partrac Ltd (2010) for conditions at the Inch Cape OWF site specifically (Table 7-7). These studies indicate waves >4.5 m are expected to occur only once per decade, although total sea heights are somewhat higher. Additional data are presented from HR Wallingford (2009b) and Partrac Ltd. (2010) specifically in relation to the waves coming into the site from 45^{o}, and these indicate very high (>10 m) individual waves. In addition to this, the Angus Shoreline Management Plan lists a 100-year return period extreme wave height of 11.9 m at a distance of 9 km offshore from Montrose (Angus Council, 2004). This report also lists the 100-year return significant wave height 30 km offshore from the Tay Estuary as 8.95 m.

Table 7-8 :Compilation of offshore extreme total sea and swell conditions statistics.

Return period (years)	Total sea significant wave height (m)[1]	Swell sea significant wave height (m)[1]	Significant wave height (m), from °N, 45°	Maximum individual wave height (m), from °N, 45°	Significant wave height (m), from °N, 45°	Maximum individual wave height (m), from °N, 45°	Zero Crossing Period (s)
	Ramsay & Brampton		HR Wallingford		Partrac		
1	6.23	3.56	5.7	10.2	4.5	8.4	14
10	7.62	4.49	6.9	12.4	6.94	10.9	24
100	8.95	5.36	8.0	14.5	8.94	13.6	26

Note: Source: Ramsay & Brampton (2000a and b), HR Wallingford (2009b) and Partrac (2010). Partrac's data relate specifically to the Inch Cape location.
[1] Location is 30 km east of the mouth of the Tay estuary.

7.3.3 Wave Climate in the Development Area

As offshore waves move from deep water into shallower water a number of important modifications occur as they begin to interact with the seabed. These are:

- Shoaling and refraction (depth and current);
- Energy loss due to breaking;
- Energy loss due to bottom friction; and
- Momentum and mass transport effects.

Waves affected in this way are normally termed shallow water waves. Whereas there are data sources which derive from modelling of the wave climate from Met Office wind data records, the data collected as part of the oceanographic monitoring campaign (Table 7-7) represents measured parameters at the two sites which are to be developed. Thus, these data reflect and include the above processes, if indeed they occur. From consideration of the incident wave heights and periods it is likely that at each site some interaction of the waves with the seafloor will occur, with consequent geometric modification as well as the potential to generate sediment transport, for at least a proportion of the time. However, as the bathymetry within the outer Firths does not provide any dramatic shoaling (to < 20 m) or deepening, it is considered unlikely that significant wave refraction will occur (except possibly for the very largest waves which might occur; see Table 7-8), nor is wave breaking likely across the region (except at the shoreline). However, refraction and wave breaking will occur closer inshore around the shoreline periphery of the outer Firths region (e.g. Al Mansi, 1990 for the Angus coastline).

8 SEDIMENT REGIME

8.1 INTRODUCTION

The contemporary sediment regime across the Outer Forth and Tay Estuaries comprises of a number of inter-related elements, including; populations of surface seabed deposits, mobile bedforms, suspended material semi-resident in the water column and various sources and sinks for different sediment types. The behaviour of these various sediment populations depends on their respective response to the applied hydrodynamic forces of waves, tides and potentially also on river discharge.

Mobilisation of sediments from the seabed can be expected when the shear stress effects from the applied hydrodynamic conditions exceeds a certain threshold relevant to the specific material type. Transport then occurs in the direction of the sustained flow regime until shear stress levels drop below a threshold for maintaining transport and the material drops out of suspension. For larger sediment fractions the mode of transport may be along the seabed as bedload, which can give rise to bedforms. The combination of waves and currents provides the most significant influence to the initiation of sediment transport. Fine sediments (e.g. silts and muds) tend to be transported as a suspended sediment load and may remain in suspension for long periods throughout the tidal cycle, whereas coarser sediments (e.g. sands) may only be transported at time of peak flow and move as either bedload or suspended load. The transport potential of bottom sediments is critical to understanding of the impacts on the geomarine environment of offshore structures, as their presence invariably leads to an amplification of the local sediment transport rate to produce such effects as scour or bedform migration.

8.1.1 Dredged Sediments

Fine sediments in suspension may also be due to offshore disposal activities following dredging of navigation channels and port and harbour berths. There are three designated disposal areas in the vicinity of the proposed wind farm developments: Bell Rock, Anstruther and St Abb's Head (Table 7-8; Figure 8-1) [2]. Unfortunately, an assessment of water column sediment loadings in relation to these sites is not available as no concentration data are collected by the regulator in the vicinity of the disposal sites.

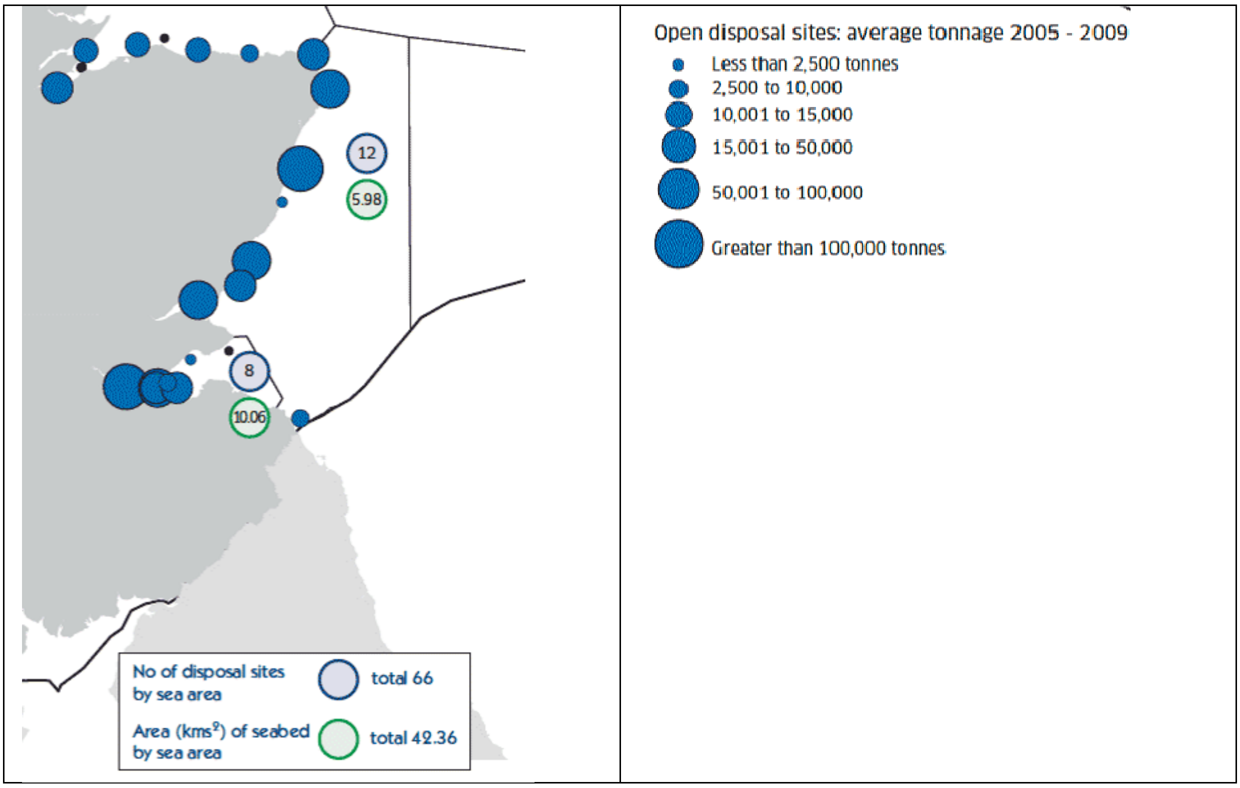
Table 8-1 : Designated disposal areas, 2006 in the vicinity of the proposed wind farm developments.

Area of dredging	Licensed tonnage	Tonnes disposed	Reporting area
Aberdeen, Montrose, Arbroath, Dundee & Berwick1, St Abbs, Bell Rock	688,755	302,463	East Coast Scotland
Upper Forth Crossing, Aanstruther, Kincardine, Grangemouth, RNAD Crombie, Rosyth, Royal Forth Yacht Club, Leith,	4,739,699	1,087,908	Forth

Note: Weights as wet tonnes

[2] The Scottish Government's Second National Planning Framework identifies future port developments at Grangemouth and Rosyth. Associated dredging (and disposal) may be required.

Figure 8-1 : Locations and average tonnage disposed at open sites along the Scottish east coast and outer Firths region (2005 and 2009).



Source: Marine Scotland.

8.2 FLUVIAL SEDIMENTARY INPUTS

Various rivers and estuaries discharge into the study area with the freshwater inputs contributing to the overall hydrodynamic regime. SEPA monitors flow in these rivers with gauging stations at strategic points commonly upstream of tidal limits. Table 8-2 summarises details of freshwater input from the main rivers discharging into the development area.

It is evident that the Rivers Tay and Forth are the dominant sources of freshwater flow into the proposed development area, accounting for around 97% of the total mean flow. The table is not exhaustive in providing a list of river discharges into the development area; however, our understanding is that the remaining rivers contribute negligible freshwater inputs. In relation to the locations of the proposed wind farms, it is considered that the volumes of freshwater received into the inshore zone are small in relation to the tidal (marine) volume and the conclusion is that these do not form significant freshwater influences.

Sediment concentration data have been provided by SEPA for the three main rivers (Table 8-2), and these reveal universally low concentrations (< 50 mg l^{-1}, maximum). The gauging sites are upstream (beyond the tidal limit) and therefore represent the true sedimentary inputs from the river catchment to the estuarine zone and beyond (i.e. into nearshore coastal waters). The data indicate delivery of low sediment loads, with highly similar mean concentrations amongst the three rivers. Since the freshwater inputs into the coastal region are negligible it may be concluded also that input of fluvial sediments is also negligible.

Table 8-2 : River and suspended solids inputs to the development area.

River	Catchment area (m^2)	Mean flow ($m^3 s^{-1}$)	95% exceedence ($m^3 s^{-1}$)	10% exceedence ($m^3 s^{-1}$)	TSS Gauging Sation	Monitoring Period	Total Suspended Solids Conc. ($mg\ l^{-1}$)		
							Min	Max	Average
Forth	1036.0	46.98	5.50	115.50	Craigforth	17.01.10 – 22.11.10	1	28	10
Tay	4587.1	169.20	43.04	335.20	Queens Bridge	4.02.08 – 22.08.11	1	26	5
Eden	307.4	3.93	0.96	8.06	Kemback	17.08.11 – 20.09.10	2	43	10
Total	5930.5	220.11	49.5	458.76					

Source: National Rivers Archive website, 2009; query to SEPA July, 2011

Although not based on hydrologic sediment concentration data, Gatliff et al., (1994) assert that any fine sediments issuing from the major rivers are either trapped in the estuaries or deposited in nearshore areas of muddy sediments. An area of muddy sand occurs offshore of Arbroath and Lunan Bay (see Figure 6-1, section 6) and similar (inshore) areas are found in the Firth of Forth. Additional data from Balls (1992) indicates very low (~ 20 mgl^{-1}) concentrations of suspended sediments in the outer Firth of Forth area, which suggests that riverine sediment (mud), here, does not transport offshore in significant quantities and it not therefore judged to be an important component of the offshore sediment budget.

Some limited sediment concentration data were collected within the FTOWDG oceanographic monitoring campaign (Table 8-3). Although these data are not time-stamped i.e. they contain no information about when in the tidal cycle they were collected, the data indicate universally extremely low concentrations, rather lower than the value quoted by Balls (1992), and consistent perhaps with a farther offshore location. It can be assumed that the conditions were calm during sampling (in order that good quality samples could be collected), and thus these can be regarded as fair-weather summer-time concentrations. Maximum concentrations of 8 mg l^{-1} were recorded, but in many instances near bottom concentrations of 3 mg l^{-1} or less were recorded.

Table 8-3 shows the results of particle size analysis on sediments captured by a near-bottom sediment trap located in the Neart na Gaoithe site during the metocean survey campaign. These indicate that although particles up to 250 µm are found in suspension, these are rare and the most frequent size is within the range 3.9 - 15.59 µm (i.e. v. fine to fine silts). This indicates, at least in summer months when these samples were collected, only fine-grained sediments are found in the water column at the Neart na Gaoithe site.

The source of this material cannot be inferred from this data. Sediment may derive from fluvial sources (although not considered a dominant source, as described above), from autochthonous sources such as plankton blooms, or from resuspended/eroded bottom sediments. Mineralogical and tracer studies by McManus *et al*., (1993) directly endorse the ‘bottom sediment source’ view, with most offshore sediments found to be derived from erosion of Quaternary sediment lenses.

Table 8-3 : Suspended solids concentration at the Neart na Gaoithe site

Depth	Suspended Solids Concentration mg l^{-1}
Near bottom	<3
25 m	<3
10 m	4
Near bottom	8
25 m	3
10 m	8
Near bottom	3
25 m	3
10 m	3
Near bottom	4
25 m	3
10 m	7
Near bottom	<3
25 m	<3
10 m	<3
Near bottom	4
25 m	4
10 m	5

Note: data collected on 12.07.10 during the oceanographic monitoring campaign.

Table 8-4 : Distribution of particle size within a sediment trap sample at the Neart na Gaoithe site.

Size Fraction	%
Grain Size Fraction : 125 to 249 microns	0.87
Grain Size Fraction : 63 to 125 microns	5.38
Grain Size Fraction : 32 - 62.9 microns	11.2
Grain Size Fraction : 15.06 - 31.99 microns	25
Grain Size Fraction : 7.8 - 15.59 microns	30.9
Grain Size Fraction : 3.9 - 7.79 microns	17.9
Grain Size Fraction : > 63000 microns	0
Grain Size Fraction : > 8000 microns	0
Grain Size Fraction : < 63 microns	93.8
Grain Size Fraction : < 20 microns	68.1
Grain Size Fraction : <3.9 microns	8.86
Particle Diameter : Mean	0.021
Particle Diameter : Median	0.013

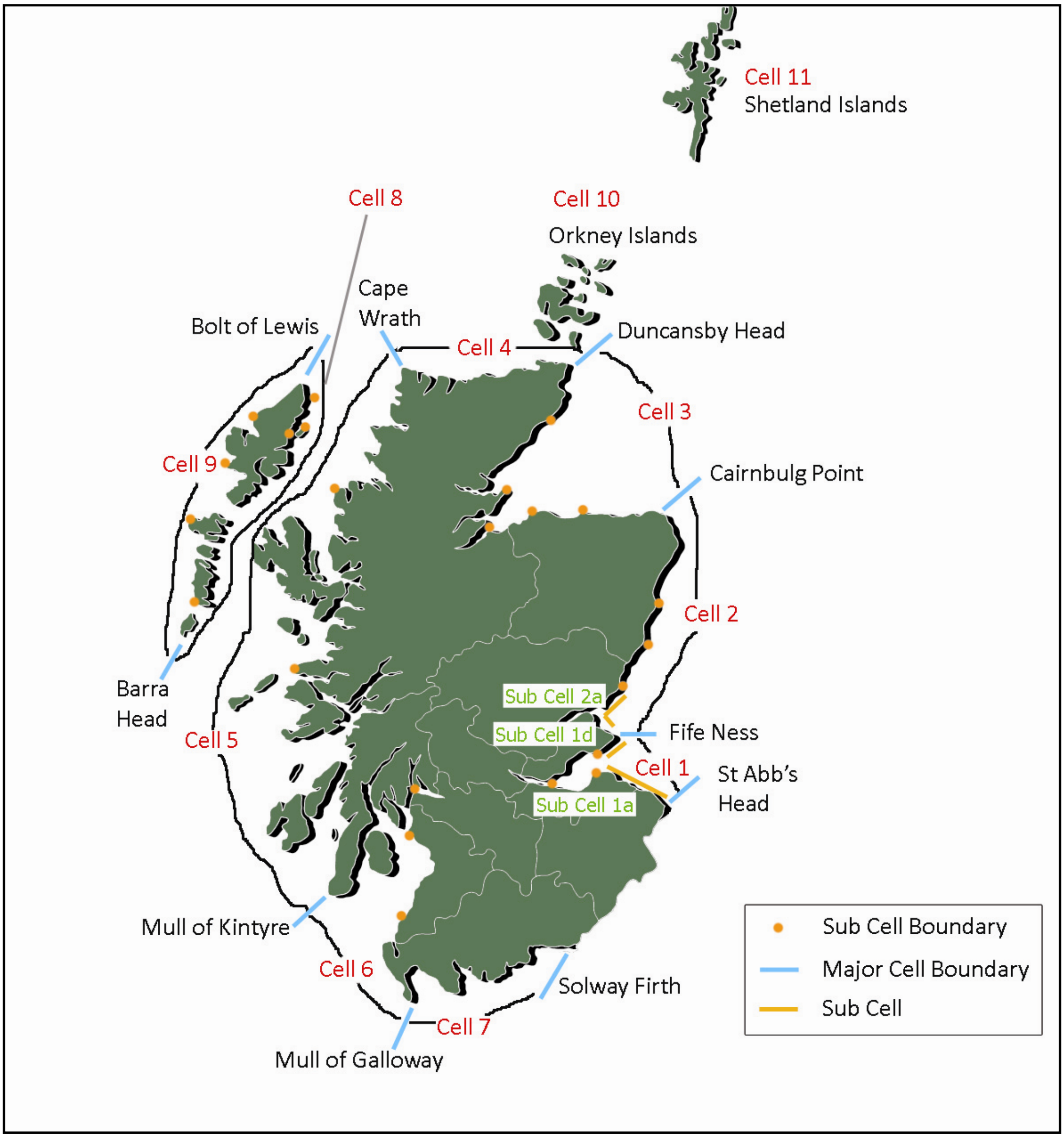
Source oceanographic monitoring campaign.

8.3 SHORELINE PROCESSES AND COASTAL CELLS

The Scottish coastline exhibits significant geomorphological features (e.g. raised beaches, sand spits, exposed cliffs and rocky shorelines), which have the potential to be affected by changes in coastal processes associated with offshore wind development. These physical features reflect the interactions between sea level change, isostatic adjustments, differences in lithology and changes in the sediment supply to the coast since the last glaciation. Coastal erosion and sediment transport at the shoreline is driven through a combination of tidal currents, breaking wave impacts, wave-induced longshore currents and direct wind shear (e.g. erosion of dune systems).

By studying patterns of longshore drift (i.e. the movement of beach sediment) around coastlines, it is apparent that there are points or features around or through which beach forming materials such as sand and gravel are not transported. Such features may be used therefore to demarcate stretches of coastline which are effectively self-contained in terms of beach sediment movement. Additional criteria are also used, such as (similar) coastline orientation, physical character and contiguous geology. The stretches of coastline between these points or features are known as 'coastal cells' (Ramsay and Brampton, 2000a, b). Often a feature within a coastal cell, such as a headland, may block movement of beach material under most conditions but will allow occasional transport under exceptional circumstances (e.g. prolonged gales from a particular direction); these are known as 'sub-cell's. Coastal cells frequently contain many sub-cells some of which may comprise estuarine environments. Scotland is divided into 11 coastal cells. Figure 8-2 shows the coastal cells of importance to the proposed OWF sites.

Figure 8-2: Major coastal cells around the Scottish coastline, including sub-cells.



Note: redrawn from Ramsay and Brampton (2000a, b).

An understanding of the general baseline directions and rates of sediment transport within these cells and at the shoreline within cells is fundamental to being able to establish if there may be changes to the shoreline sediment regime as a consequence of OWF developments; for example, by increasing or reducing the supply of sediments to the coast, or through modification of the wave climate.

From the point of view of the proposed OWF developments, consideration of the coastal oceanography, and coastal and littoral sediment processes within Sub-cells 1a and 1d are largely relevant to the Neart na Gaoithe development and within Sub-cell 2a for the Inch Cape development (Figure 8-2).

Sub-cell 1a stretches from St Abbs Head to North Berwick and comprises 13 coastal process limits (mainly headland – headland sub-divisions) (Figure 8-2). It is a largely, northeast facing rocky coastline exposed to waves dominantly from O^o (N) to 130^o. The coastal oceanographic conditions, including extreme offshore wave conditions (Tables 7-7 and 7-8), have been summarised in Section 6.3. The inshore wave climate is undoubtedly complex, due to the coastline geomorphology and complex nearshore topography, and the inshore bathymetry narrowing and steepening with distance south.

Glacial and post-glacial sediments are generally thin along most of this sub-cell, however extensive deposits form beaches around Belhaven Bay, Ravenshaugh and Barns Ness. There is very little contemporary supply of sediment to the coastal zone, the many bays are largely self-contained in terms of sediment transport and there is little regional net sediment movement along the sub-cell coast due largely to the orientation of the coastline. Ramsay and Brampton (2000a) note that any erosion induced by severe winter storms is likely to leave the sediments still within the immediate beach system, albeit perhaps sub-tidally located. The broader, intertidal regions to the northern end of the sub-cell, in addition, act to dissipate incoming wave energy at the shoreline thereby reducing the importance of longshore sediment transport.

A far greater level of detail on beach and coastal geomorphology of sub-cell 1a, not reviewed here, may be found within the Shoreline Management Plans for the east Lothian coastline (Babtie/East Lothian Council, 2003 [3]).

Sub-cell 1d stretches from Elie in the west to Fife Ness in the east (Figure 8-2). Largely the shoreline comprises a continuous rock platform for the length of the sub-cell. Beach areas are generally small pocket bays with thin sand, shingle or cobble cover. Although some mobilisation of sediment may occur during storm events at higher (surge) water levels, the rock platform largely protects the shoreline and much of the wave energy is dissipated around the -5 m (ODN) contour (Ramsay and Brampton, 2000a). The orientation of the coastline within the sub-cell means that waves from the regionally dominant direction (i.e. 20 to 60^o N; see Section 6.3) have little direct influence on the coastline. Restricted fetch lengths will limit the severity of wave conditions from the southwest, and waves from the southeast are generally less frequent and generally small. The combination of these factors means the sub-cell is generally largely stable in the short-to-medium term, with only occasional erosion of the rock strata to produce more local sediment.

The Inch Cape development site is offshore Arbroath and borders on Coastal Cell 2 (Sub-cell 2a). Cell 2 stretches from Fife Ness to Cairnbulg point in Aberdeenshire. These northern- and southern-most points represent significant changes in the orientation of the coastline, across which sediment movements are judged to be unlikely. Sub-cell 2a stretches from Fife Ness to Deil's Head and is inclusive of the outer Tay estuary area. The seabed sediments in the region comprise extensive deposits of sands and gravels which were laid down by outwash processes during the last glacial retreat (~15,000 years BP), and which has provided much of the unconsolidated raw materials which have been transported and reworked by river, wind, and wave processes to create the present day coastal sediments and landforms. Inshore flow patterns are complicated through the interaction of freshwater from the Tay interacting with saline seawater, through shifting shallow sandbanks and channels and through

[3] http://cmis.eastlothian.gov.uk/CMISWebPublic/Binary.ashx?Document=4117.

the presence of the Fife peninsula which rotates the flood currents in a clockwise direction. The coastal oceanographic conditions, including extreme offshore wave conditions (Tables 7-7 and 7-8), have been summarised in Section 6.3, with swell wave comprising the dominant component of the wave climate in the region. Depending on the orientation of the coastline, waves from both the NE and SE quadrants can have a significant impact on the processes at the shoreline, although for some areas extensive intertidal areas (e.g. at Tenstmuir, Fife) and shallow sandbanks (outer Tay estuary) protect the shoreline from severe storm wave erosion.

Littoral processes are dominated by waves and currents. The transformation of waves as they approach the shoreline has been assessed by Halcrow (1998) at Montrose, and also by Ferentinos & McManus (1981) along the Arbroath to Fife Ness coast. These studies showed that waves from the northeasterly quadrant resulted in a strong southward flowing longshore current between Arbroath and Buddon Ness and waves from the southeast producing the opposite effect, a strong northerly flowing longshore current along the shoreline north of St Andrews. The relative frequency of waves from differing directions (see Figure 8-3) governs directly differences in shoreline sediment transport rates, meaning that southward directed transport rates are generally larger of the two directions. Whereas Tentsmuir Sands, at the southern edge of the mouth of the Tay estuary, is accreting, widespread erosion is occurring on much of the coastline of North Fife and Angus (and consequently much of the shoreline has been protected by hard structures (e.g. concrete seawalls). This is an important feature to establish as it provides a dynamic baseline against which to assess realistic changes in shoreline erosion and coastal processes as a result of the construction of offshore structures.

Ramsay and Brampton (2000b) state that the most seriously affected areas are the southern coastline of the Eden estuary (which shows signs of both accretion and erosion), the Monifieth to Barnhill frontage and the Carnoustie frontage. Episodic storm erosion is also occurring along most of the frontage to the south of St Andrews and to the north of Carnoustie. HR Wallingford (1989) noted in a detailed study of littoral processes that erosion dominated the northern part of Carnoustie Bay between 1969 and 1988 with the transport of material towards the south and driven by episodic wave action. The erosion may be related to increases in southeasterly wave conditions, which serves to illustrate a sensitivity to wave direction and magnitude, and also points to medium term changes in wave climate as an important (and fundamentally uncontrollable) natural phenomenon governing coastal sediment stability.

Fluvial sediment, such as from the Tay, the North and South Esks, or the smaller river systems e.g. Lunan Water, that discharge along the Angus coast now supply very little sediment to the Angus beaches.

Ramsay and Brampton (2000b) summarise in greater detail a number of studies into coastal processes within Sub-cell 2a, in particular on the northern shores, and specific highly detailed information is available within Angus and Fife Shoreline Management Plan documents (Posfords, 1998). Further information on sediment transport along the Angus coast has been discussed in a number of previous studies and reports. These include numerical modelling of sediment transport at Montrose (HR Wallingford, 1995; Halcrow, 1998 [4]), for the outer Tay Estuary (Ferentinos & McManus 1981; Sarrikostis and McManus

[4] In Chapter 2.1 Wind, wave & tidal characteristics. Angus Shoreline Management Pan. http://www.angus.gov.uk/ac/documents/roads/SMP/2-1.pdf. Direct reference not available.

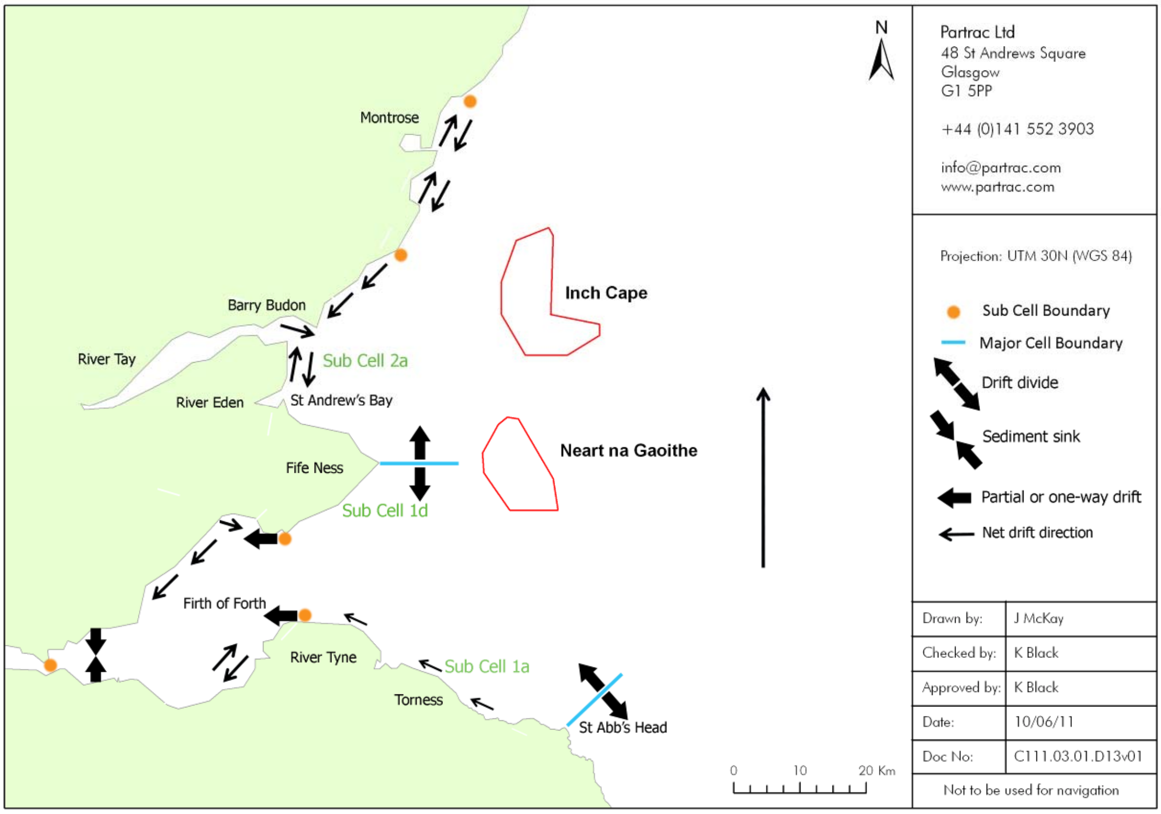
1987), and for Monifieth Bay (Al-Mansi, 1989). More information on the coastal morphology and processes on the Angus coast can be found in The Beaches of Tayside (Wright 1981). A considerable amount of foreshore monitoring data also exists (through local council schemes), not reviewed here, but these are available to this study.

8.4 Conceptual Understanding of Regional Sediment Regime

A conceptual understanding of the regional and local sediment regime has been developed from a review of available evidence. Figure 8-3 presents this in schematic form. This type of assessment aims to interpret a qualitative behavioural model from available evidence. Primary evidence used in the development of the conceptual model includes:

- the offshore tidal current symmetry;
- the dominant wave directions;
- bedform morphological features such as sand waves and megaripples; and
- shoreline longshore drift evidence.

Figure 8-3 : Schematic of regional coastal sediment transport pathways (bedload) in the outer Firths region.



Source: Adapted and modified from HR Wallingford (2009a).

Review of the information and data contained within Angus, Fife and East Lothian Shoreline Management Plan documents, local studies and the evaluation of coastal cells shows differences in sediment transport and drift rate around the periphery of the outer Firths region. Along the East Lothian shoreline (i.e. to the south and west of the Neart na Gaoithe development) the evidence indicates there is little regional net sediment movement along the coast due largely to the orientation of the coastline. Along the southeast Fife coastline transport rates are similarly very low but due to a combination of a dominantly rocky shore geomorphology, highly limited sediment supply and exposure to only small, infrequent waves. Conversely, the shoreline regions to the west of the Inch Cape development are active in terms of shoreline erosion. The Angus coastline in particular, which is exposed to both swell and local waves from the east, suffers southwards directed variable longshore drift in most soft-sediment areas, and consequently the shoreline is protected in many areas. The patterns and rates of drift are complicated by a complex inshore bathymetry, which itself is variable through time under wave action.

Farther offshore, sand transport rates are relatively low over much of the central North Sea as a result of the lower tidal currents in the deeper water depths (Kenyon and Stride, 1970). Much of the seabed in this area is covered by sheets of generally featureless sand, suggesting that the hydrodynamic conditions are not sufficient to cause significant movement of sediment (Gatliff *et al*., 1994). If (sand) sediments are mobilised, these are likely the result of very large, very infrequent storms (1-2 times per year) which give rise to large oscillatory flows at the seabed (Stride, 1981). There appears to be some movement of sand from the northeast into the Firth of Forth according to Gatliff *et al*., (1994) and there is also a locally moderate wave-induced east to west littoral drift along the southern shoreline of the Firth (HR Wallingford, 1998). There is no significant transport between the north and south shorelines of the Firth.

Across the entire outer Firths area and within each development boundary the consensus is that sediments are mobilised at least some of the time; observations of sediment colour as yellow in depths up to ~ 70 m indicate oxidised sediments and these are, therefore, at least partially mobile (Gatliff *et al*., 1994). Owens (1981) suggests the combination of tidal and storm wave induced currents has the capacity to mobilise sediments up to gravel grade in such depths, especially on topographic highs, although there are areas of the seabed which are relict and those which have been exhumed through erosion but are stable. Winnowed gravels are frequently found on topographic highs such as banks, and around the periphery of these structures. Sediment transport may be more prevalent offshore Firth of Tay (i.e. in the vicinity of the Inch Cape site) where the tidal currents are slightly stronger in comparison to farther south and the region is exposed to powerful swell waves.

The direction of sediment transport, where it occurs, is largely parallel to the coast. Figure 8-1 shows how these vary, and differ directionally, within the outer Firths region. Within the Phase 1 Zone 3 area, bedload sediment transport is supposedly driven by tidal currents and is predominantly in a north-northeasterly direction. However, the residual current between the flood and the ebb is low, and so bedload sediment transport is limited (Seagreen, 2011), a supposition supported by Stride (1982). The northward transport is part of an overall general northward transport of sediment for over 250 km from around St Abbs Head up to a bedload convergence zone situated off northeast Scotland, located at the northern extremity of the coastal cell (Figure 8-1). There is also a divergent zone offshore Fife Ness as a result of dramatic changes to the orientation of the coastline (Ramsay and Brampton, 2000a).

Low residual currents may predominate at the Neart na Gaoithe site, however, there is a pronounced flood-dominant tidal asymmetry at the Inch Cape site which would drive a residual sediment transport (for both bedload and suspended load) approximately south-southwestwards.

Within the surface sediment, there is evidence of sandwaves and megaripple bedforms being present, indicative of sediment mobilisations. To the north and east of the outer Firth region, megaripple fields are noted with crest alignments normal to the predominant tidal axis (~NE-SW) (Gatliff *et al*., 1994). The BGS Seabed Sediments Tay-Forth 1:250 000 Series (1986) map indicates the presence of sinuous sandwaves/megaripples, extending as a narrow band across the central portion of the Neart na Gaoithe site. The sandwaves/megaripples are oriented WSW-ENE, and are located in the areas of both sandy and muddy sediments. A smaller band of linear sandwaves/megaripples is located just to the south of the Neart na Gaoithe site, and these are oriented mostly SE-NW.

Very little data exists on the nature and dynamics of suspended sediments in the outer Firths area. What there is indicate that the outer Firth region is characterised by very low concentrations (< 20 mg l^{-1}), due principally to highly limited fluvial input and semi-stable bottom sediments, although periodically (e.g. during summer months) regional turbidity values may rise due to biological particulates. Whilst an important component of the ecosystem these particles are eventually mineralised and form a minimal component of the sediment budget. Dumping of fine grained dredge material has the potential to temporarily elevate concentrations but no quantitative data are available. Fine-grained material introduced by rivers into the outer Firths region will be advected by the tidal currents and may to an extent follow the residual tidal circulation. Clearly, however, deposition of this material does occur over medium to long timescales as indicated by muddy bottom sediments (muddy sands) offshore of the Angus coastline and variously within the inner Firth of Forth (see Figure 5-2).

9 REFERENCES

Al-Dabbus, M.A.M. and McManus, J. (1987). Shell fragments as indicators of bed sediment transport in the Tay Estuary. Proc. of the Royal Society of Edinburgh, 92B, pp 35-344.

Al-Mansi, A. M. A., 1990 Wave refraction patterns and sediment transport in Monifieth Bay, Tay Estuary, Scotland. Marine Geology. 91 (4), 299-31.

Balls, P. W. (1992) Nutrient behaviour in two contrasting Scottish estuaries, the Forth and Tay. Oceanologica Acta 15, 261–277.

Callum, R.F., Collins, E.F, and Smith, D.E., (1997) Coastal presses and management of Scottish estuaries IV - The Firth of Forth. SNH Report No. 87, 124pp.

Charlton, J.A., McNicoll, W. and West, J.R. (1975). Tidal and freshwater induced circulation in the Tay Estuary. Proc. of the Royal Society of Edinburgh, 75B, pp 11-27.

Defra (2006). Flood and Coastal Defence Appraisal Guidance: FCDPAG3: Economic appraisal: Supplementary note to operating authorities – Climate change impacts. 9 pp.

Ferentinos, G. & McManus, J., (1981) Nearshore processes and shoreline development in St Andrews Bay, Scotland, U.K., Special Publications of the International Association of Sedimentologists 5, 161-17.

Firth of Forth and Tay Developers Group (2009). Collaborative oceanographic survey: Request for proposals: Specification and design. Tender document produced by Mainstream Renewable Power and SeaEnergy Renewables, date of issue 1 September 2009.

Gatliff, R.W., Richards, P.C., Smith, K., Graham, C.C., McCormac, M., Smith, N.J.P., Long, L., Cameron, T.D.J., Evans, D., Stevenson, A.G., Bulat, J. and Ritchie, J.D. (1994). The geology of the Central North Sea. British Geological Survey offshore regional report, HMSO, London. ISBN 0118845047.

Harrison, S.J., (1987) Climatic conditions over the estuary and Firth of Forth, Scotland. Proc. Royal Soc. Edinburgh 93B, 245-258.

Holmes, R. (1977). Quaternary deposits of the Central North Sea. 5. The Quaternary geology of the UK sector of the North Sea between 56 and 55° N. Report of the Institute of Geological Sciences, No.77/1.4.

Holmes R, Bulat J, Henni P, Holt J, James C, Kenyon N, Leslie A, Long D, Musson R, Pearson S, Stewart H, 2004 DTI Strategic Environmental Assessment Area 5 (SEA5): Seabed and superficial geology and processes. British Geological Survey Report CR/04/064N.

HSE Offshore Technology Report (2001) Wind and wave frequency distributions for sites around the British Isles. 88pp.

HR Wallingford (1998). Coastal Cells in Scotland: Cell 1 – St Abb's Head to Fife Ness; Cell 2 – Fife Ness to Cairnbulg Point. Report EX 3471.

HR Wallingford (2009a). Firth of Forth and Tay Developers Group: Collaborative oceanographic survey: Specification and design. Work Package 1 Review of existing information. HR Wallingford Proposal P8373.

HR Wallingford (2009b). Firth of Forth and Tay Developers Group, Collaborative oceanographic survey: Specification and design: Preliminary engineering design criteria. HR Wallingford Technical Note DER4539/02.

HR Wallingford (2009c). Firth of Forth and Tay Developers Group, Collaborative oceanographic survey: Specification and design: Survey methodology and programme. HR Wallingford Technical Note DER4539/03.

HR Wallingford (2009d). Coastal process scoping study Firth of Forth OWF: Neart na Gaoithe offshore wind farm. HR Wallingford Report EX 6131.

Intertek METOC (2011). Inch Cape & Neart na Gaoithe Offshore Wind Farms Coastal Processes Assessment – Hydrodynamic and Spectral Wave Model Calibration and Validation. Intertek METOC Report P1476_RN2636.

Kenyon, N.H. and Stride, A.H. (1970). The tide-swept continental shelf sediments between the Shetland Isles and France. Sedimentology, 14, pp 159-173.

Owens, R., Holocene Sedimentation in the Central North Sea. PhD thesis, University of Edinburgh.

Pantin, H., (1981) The seabed sediments around the UK. BGS Research Report SB/90/1. 47pp.

Ramsay, D.L., and Brampton, A.H., (2000a) RSM 143 Coastal Cells in Scotland Cell 1.

Ramsay, D.L., and Brampton, A.H., (2000b) RSM 144 Coastal Cells in Scotland Cell 2.

Rose, N. (1980). The Beaches of South East Scotland. Department of Geography, University of Aberdeen, for the Countryside Commission for Scotland. Reprinted 2001 by Scottish Natural Heritage as a Commissioned Report.

Sarrikostis, E. & McManus, J., (1987) Potential longshore transports on the coasts north and south of the Tay Estuary. Proceedings of the Royal Society of Edinburgh, 92B, 297-310.

Seagreen (2011) Phase 1 Scoping Report Round 3 Firth of Forth. 140 pp.

Stoker, M.S., Long, D.A., and Fyfe, J.A., (1985) A revised Quaternary stratigraphy for the central North Sea. Report of the BGS, Vol. 17, No.2.

Stride, A.H., (1982) Offshore Tidal Sands. London, Chapman. 84 pp.

UKHO (1993). Scotland – East Coast: Fife Ness to St Abb's Head. Chart No. 175.

UKHO (1996). Co-tidal and co-range lines – British Isles and adjacent waters. Chart No. 5058.

UKHO (2009). Admiralty tide tables: Volume 1 2010: United Kingdom and Ireland (including European Channel Ports). NP 201-10. 366 pp.

Wal, A., and McManus, J., (1993) Wind regime and sand transport on a coastal beach dune complex, Tentsmuir, eastern Scotland. In: Pye, K., (Ed.) The dynamics and environmental context of aeolian sedimentary systems. Geological Society, London, Spec. Pub, 72: 159-171.